British Columbia

Electrical Trades Apprenticeship Learning Resource

DC MACHINES

LEVEL 3

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ELECTRICAL TRADES APPRENTICESHIP PROGRAM

INSTALL DC GENERATING SYSTEMS

Level 3

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Chapter 1: Describe the constructional features of DC generators

Dynamo is a generic term originally given to a rotating machine that converts mechanical energy into electrical energy, primarily in the form of direct current (DC). Although DC generators are sometimes still called *dynamos*, they are more commonly placed in the family of DC machines that includes both motors and generators.

DC generators are similar to DC motors in both appearance and construction. The main difference between the two machines is the type of surrounding enclosure. Generators tend to have open frames, but motors in a working environment are usually totally enclosed.

To understand DC machines, one must be familiar with the various parts. Following is a brief description of the key parts in any DC machine.

Armature

The *armature* is the rotating part or *rotor* of the machine. The *armature core* consists of a stack of soft iron laminations that are slotted to house a set of insulated coil windings (Figure 1).

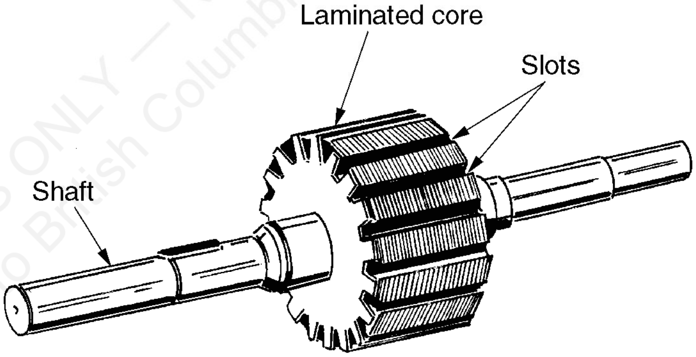

Figure 1 Armature core

The high-strength steel shaft is supported by bearings to allow uniform rotation of the complete armature assembly within the air gap.

The armature coils are generally wound with varnish-insulated magnet wire, and are protected on all sides with slot-cell insulation (Figure 2). A wedge is driven the full length of the slot to hold the coils tightly in place. The ends of each coil are connected to commutator bars.

There are three basic types of armature windings: *frog leg*, *lap* and *wave*. The coil leads for each type of winding connect to the commutator bars differently. In general:

- Frog leg windings are the most common winding used and are for moderate voltage and current applications.
- Lap windings are used in high-current, low-voltage applications.
- Wave windings are used in low-current, high-voltage applications.

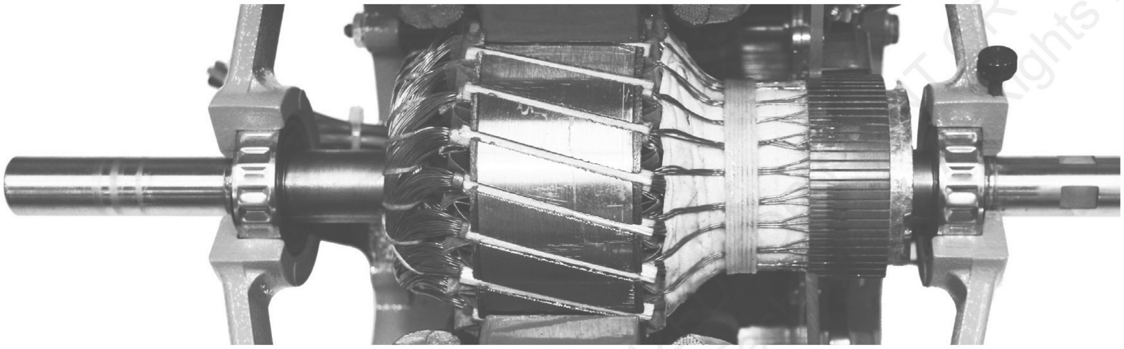

Figure 2 Complete armature

Commutator

The *commutator* is an assembly of individually insulated copper bars or segments. They are insulated from each other and the shaft by mica insulation. The brushes and commutator act together as a rotary selector switch between the armature coils and the external load. In a generator, the commutator converts the AC induced within the armature coils to a unidirectional current in the external circuit. In a motor, the direction of thrust caused by motor effect must change as the coils cross the neutral plane. To do this, the commutator ensures that the current in each armature coil changes direction as the coil crosses the neutral plane.

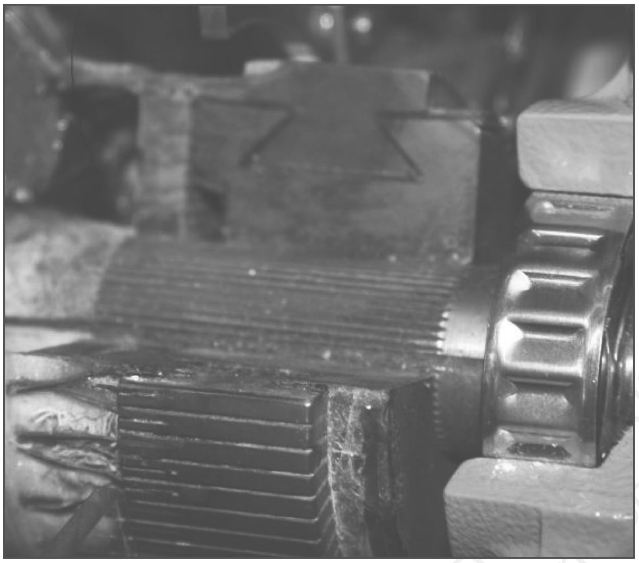

Figure 3 Cutaway of a typical commutator assembly

Brushes

The *brushes* conduct the current to or from the armature coils via the commutator from or to the external circuit. Most DC machines have brushes made of one or more of the following materials:

- Carbon
- Electro-graphite
- Graphite
- Copper graphite

The choice of brush material is based on application and cost.

The *brush holder* (Figure 4) is designed to support the brush and provide suitable pressure against the commutator surface (usually between 1 and 2 psi).

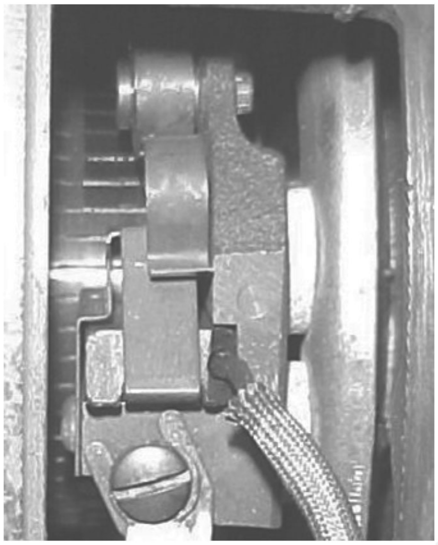

Figure 4 Typical brush holder

Field poles

Field poles provide the magnetic field in which the armature will rotate. In a DC machine, this field is provided by permanent magnets or by direct current flowing through field coils.

Electromagnetic field poles (Figure 5) consist of a soft iron, laminated core and field coils wound with varnish-insulated magnet wire.

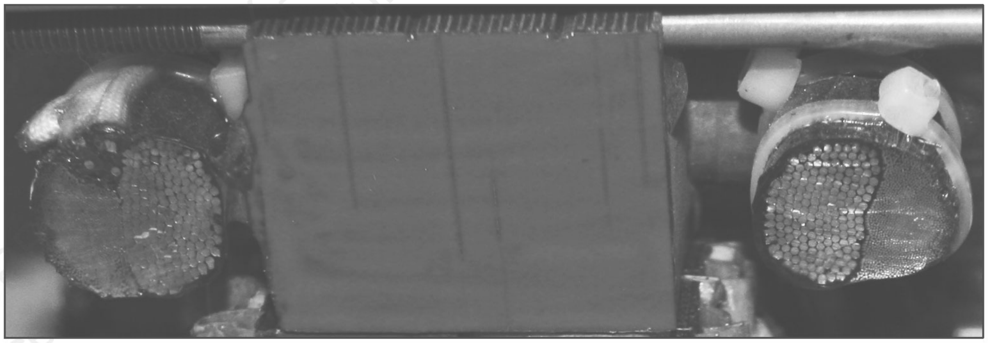

Figure 5 Cutaway of the field pole of a compound DC machine

Frame and end shields

The *frame* or *yoke* (Figure 6) provides mechanical support for the machine and forms part of the magnetic circuit between the field poles. The *end shields* are mounted at the ends of the frame and contain recesses for the armature shaft bearings.

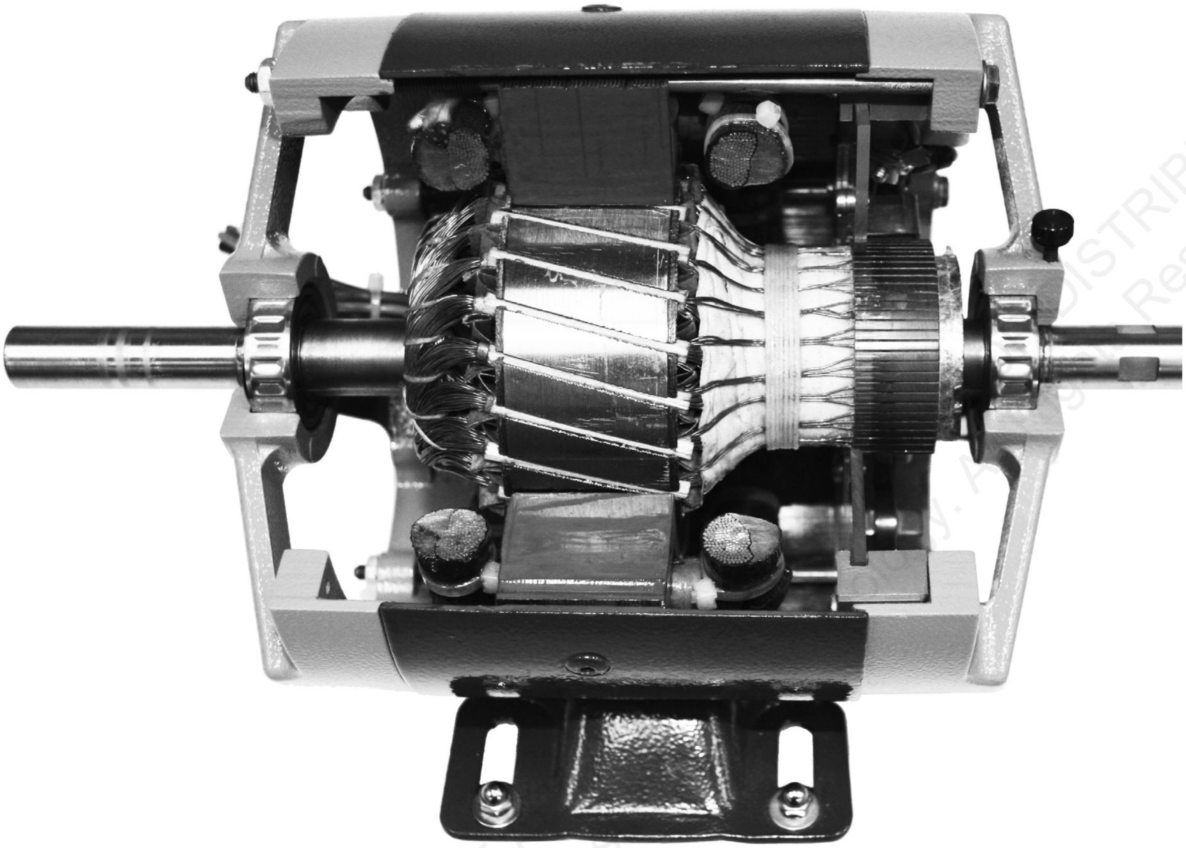

Figure 6 End shields and frame

Bearings

There are two common classes of bearings used in motors and generators: *sleeve bearings* and *ball bearings* (Figure 7).

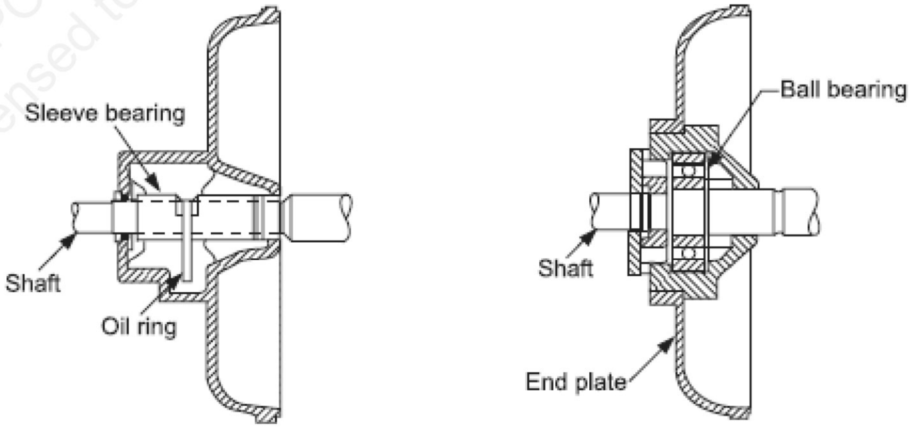
Sleeve bearing
Shaft
Oil ring
Ball bearing
Shaft
End plate

Figure 7 Cutaway showing mounted sleeve and ball bearings

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Sleeve bearings are lubricated with oil applied with an oil ring or oil-soaked wick. New sleeve bearings are usually machined under-size and require reaming for proper fit. Ball bearings are lubricated with grease and may be open or sealed. *Sealed bearings* are factory lubricated for the life of the bearing. *Open bearings* require grease nipples in the end shields. Proper lubrication will greatly extend the operating life of a bearing.

Take care not to over-grease the bearings of rotating machines. This can produce heat and shorten bearing life.

☑ Now do Self-Test 1 and check the answers.

Self-Test 1

1. What is the main difference in the construction of a DC generator and a DC motor?

2. The rotating part of a DC generator is called the ______________________________ .

3. What are the three basic types of armature windings?

4. Which armature winding is used in high-current, low-voltage applications?

5. What is the electrical function of the commutator?

6. List the common materials used in making brushes.

7. Suitable brush pressure is usually between __________________________________ and _________________ psi.

8. Describe the function of field poles.

9. DC machines use ____________________ or ______________________ bearings.

10. Grease nipples in the end shields indicate that the machine contains _________________ bearings.

Chapter 2: Describe the operating principles of generators

Generators are machines that transform mechanical energy into electrical energy. They work under the principle of Faraday's law of electromagnetic induction ($E = \beta l v$). The term *field excitation* refers to various methods of establishing and controlling the magnetic field so that induction occurs.

Permanent-magnet field poles

Small generators called *magnetos* use permanent magnets to provide the magnetic field. The voltage generated by magnetos is comparatively small due to the low flux density. In addition, it is not possible to vary the generated voltage by varying the strength of the magnetic field. These factors limit the application of magnetos. Common uses include ignition circuits for small gas engines, non-digital tachometers and meggers.

Electromagnetic field poles

Electromagnetic field poles provide a much higher and more controllable flux density than permanent magnets. The current required to excite the field windings or coils may be obtained in two ways:

- From a DC source external to the machine (*separately excited*).
- From the armature of the generator itself (*self-excited*). In self-excited generators, the field coils may be connected either in series or in parallel (shunt) with the armature. Series and shunt windings differ considerably in construction.

Series field windings

Series field windings are connected in series with the armature. Therefore, the winding must be of a sufficient gauge to carry full armature current. For this reason, series windings are made of a few turns of large-gauge wire (Figure 1).

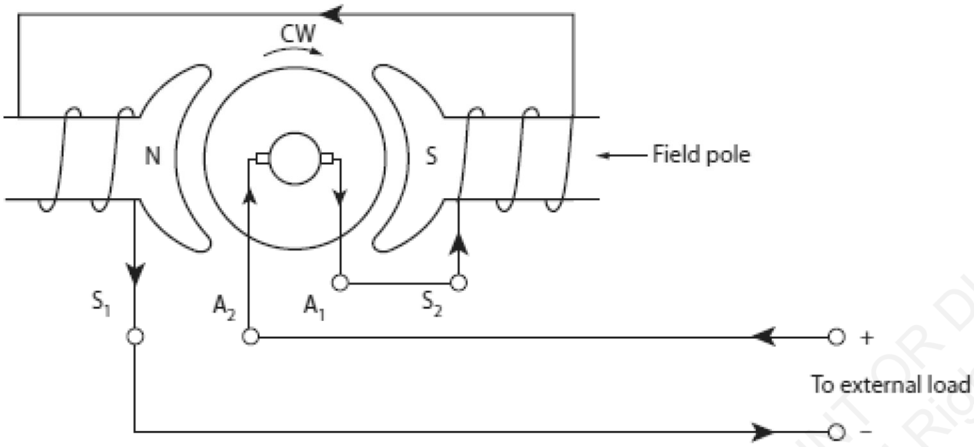

CW
N
S
Field pole
S_1
A_2
A_1
S_2
+
To external load
–

Figure 1 Series generator

Shunt field windings

A shunt winding does not need to carry high current and is made of a large number of turns of small-gauge wire. The high coil resistance results in much lower current in the field circuit. This low current through a large number of turns is sufficient to provide a magnetomotive force (ampere-turns) capable of creating the necessary magnetic field. The lower current makes it possible to control generator voltage with a rheostat in the shunt field circuit (Figure 2).

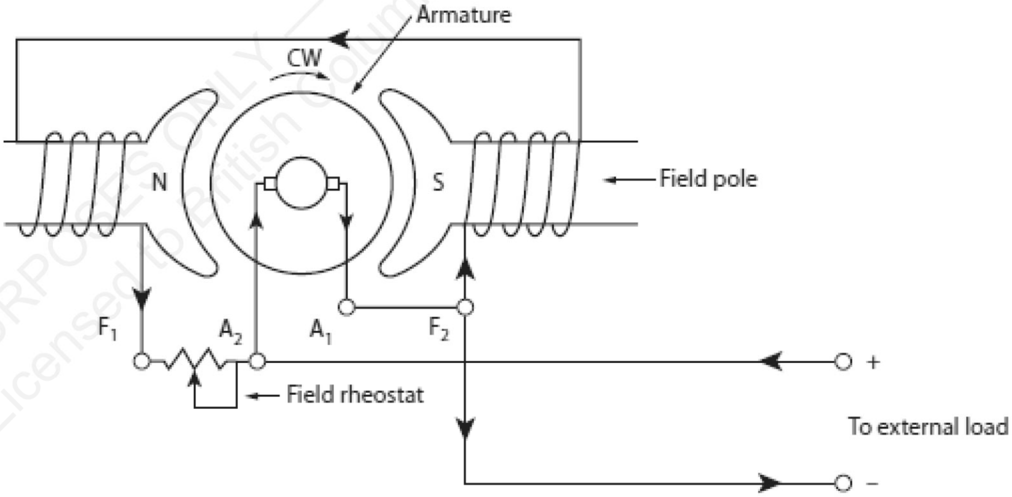

Armature
CW
N
S
Field pole
F_1
A_2
A_1
F_2
Field rheostat
+
To external load
–

Figure 2 Shunt generator with field rheostat

Series and shunt windings

DC machines often have both a series winding and a shunt winding, wound in the same direction on the same field core (Figure 3).

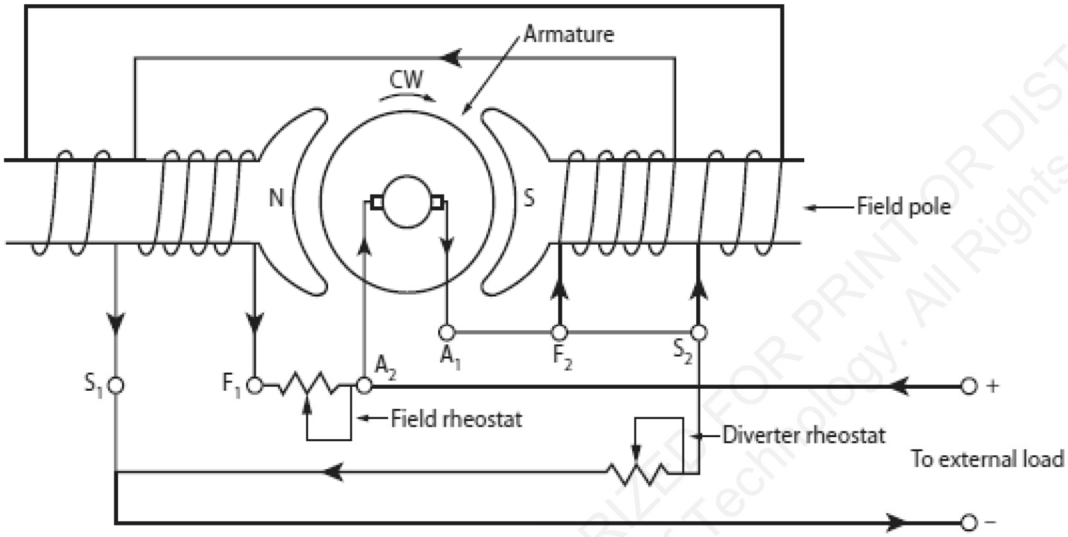


Figure 3 Compound generator with series and shunt windings

Separately excited fields

The field current for separately excited generators is derived from an external source such as a battery, rectifier circuit or separate DC generator. Therefore, construction is the same as for shunt field windings.

Self-excited fields

Most DC generators derive their field current from the armature of the machine itself and so are called *self-excited generators* (Figure 2). At the moment that the generator starts to rotate, no voltage is available to produce field current. Residual magnetism must be present in the field core to start the process of building up voltage.

Requirements for voltage buildup

Earlier it was established that Faraday's law of electromagnetic induction is expressed by the formula $E = \beta lv$. (This relationship derives from the fact that 1 volt will be induced in a conductor if it is cutting a magnetic field at a rate of 1 weber per second.)

Since the voltage induced in a conductor depends upon the rate at which it is cutting flux, it is possible to determine the total emf generated in an armature. This generated voltage is a function of the following:

- Number of poles

- Flux per pole
- Rotational speed of the armature
- Number of paths
- Total number of active conductors on the armature

For any given machine, the number of poles, paths and active conductors is fixed. Their influence on the generated voltage can be represented by a constant (k). The numerical value of this constant will change from machine to machine. The generated voltage can now be expressed by the formula

$$E_g = k\Phi N$$

where:

E_g = generated voltage in volts k = constant

Φ = flux (excitation) in webers

N = rotational speed in revolutions per minute (rpm)

In practice, the factors represented by the constant (k) are not known. However, the formula shows that the generated voltage is directly proportional to the product of flux and speed.

Example: A generator running at 900 rpm has a generated voltage of 100 V. If the excitation remains the same and the speed is increased to 1800 rpm, what is the generated voltage?

Since E_g is proportional to the product of flux and speed, and flux did not change, then the voltage is directly proportional to speed only.

The speed doubled to 1800 rpm; therefore, the voltage doubled to 200 V.

Residual magnetism

At the instant of start-up, the speed of a generator is zero, and so the generated voltage is also zero. Because a self-excited generator requires armature voltage to produce field current, there would be no flux for the conductors to cut and no voltage buildup. This problem does not exist, however, if residual magnetism is present on the field poles.

As the armature starts to turn, the following series of events occurs:

- The conductors cut the weak residual field, generating a low voltage.
- In turn, this voltage causes a low current to flow in the field windings, which increases the field strength of the poles.
- The increase in flux causes an increase in voltage, resulting in higher field current and even stronger field strength.
- The process continues until the generator reaches its no-load voltage (E_g).

A generator that has been out of service for an extended length of time may lose its residual magnetism. If there is no residual magnetism, a process called *flashing the field* can be used for start-up. In this process, a separate DC source (connected with the proper polarity) is used to cause a brief current surge in the field coils. This re-establishes the residual magnetism in the field core. Before flashing the field, disconnect a shunt field from the low-resistance armature.

Direction of rotation

The direction of the induced emf in the armature conductors is a function of the direction of the magnetic field and the direction of rotation of the armature (Fleming's left-hand rule). It is possible that the direction of rotation may be incorrect for the polarity of the residual magnetism. In this case, the generated voltage produces a field current that strips away the residual magnetism on the poles. As a result, the voltage fails to build up.

It is not usually possible to reverse the direction of the prime mover, which could be an internal combustion engine or a turbine. The simplest solutions are to re-flash the field for the opposite magnetic polarity or to reverse the connections between all field coils and the armature.

Critical field resistance

To achieve voltage buildup, the residual magnetism must generate enough voltage to increase the strength of the magnetic field poles. The field current depends on the voltage across the field coils and on the resistance of the field circuit. There exists a critical value of field resistance, which limits field current and prevents voltage buildup.

Figure 4 shows these relationships. If field resistance is held constant, a plot of field current versus terminal voltage produces a straight line. Flux produced by field current is not linear, as shown by the field saturation curve. For buildup to occur, the field resistance curve must lie below the saturation curve.

It is common to control generated voltage with a rheostat in the field circuit. As resistance in the field circuit is increased, the slope or steepness of the field resistance curve increases and may move to the left of the saturation curve. When this happens, there is not enough field current for voltage to build up.

To ensure that voltage builds up during the start-up process, set field rheostats to their minimum value of resistance.

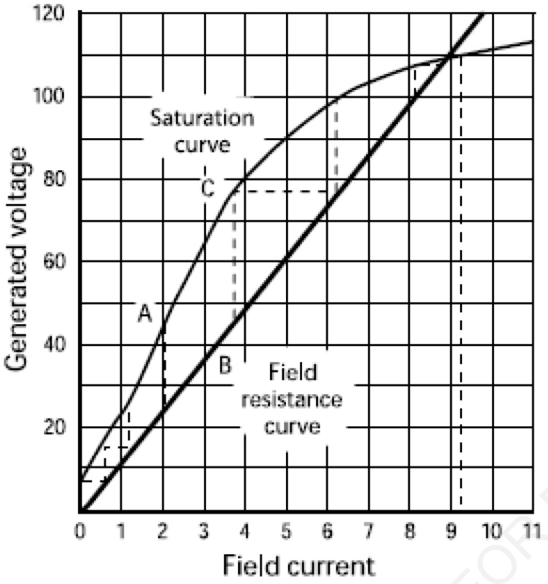


Figure 4 Field saturation and resistance curves

Prime mover speed

Generated voltage is proportional to the product of field flux and armature speed ($E_g = k\Phi N$). If the speed is too low, voltage buildup may fail.

Armature reaction

When an armature is delivering current to a load, a magnetic field surrounds the armature conductors. If uncorrected, the armature field will distort the main field created by the field poles. This *armature reaction* is one significant factor that influences the terminal voltage of a DC generator. It also impairs commutation by severely affecting the physical condition of the brushes and commutator.

To understand the interaction of the field around the armature conductors with the main field, it is useful to examine each separately.

Figure 5 shows a cross section of the armature field flux in a two-pole generator that is rotating clockwise. To simplify the illustration, the commutator, brushes and connected load are not shown.

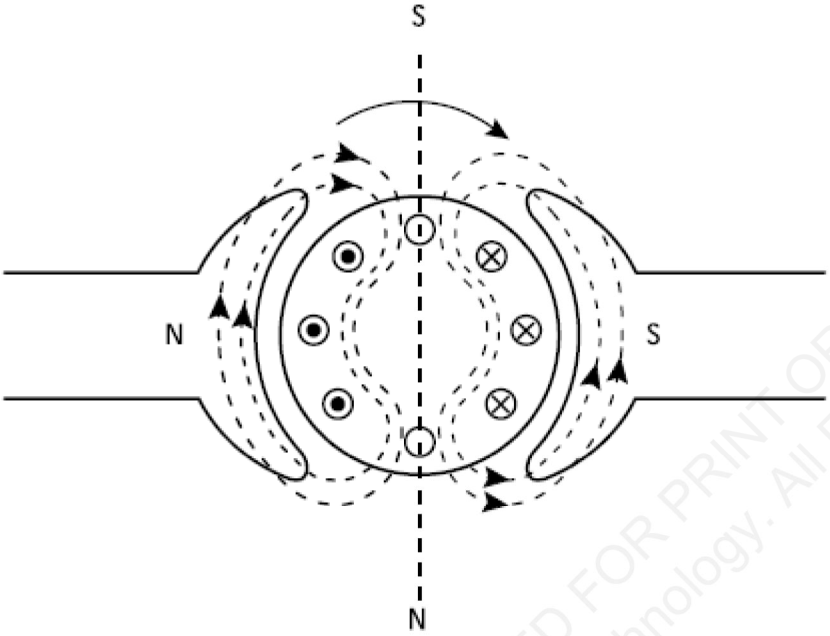


Figure 5 Armature field flux in a two-pole generator

Applying Fleming's left-hand rule, the induced emf drives current:

- Out of the page in the conductors on the left of the neutral plane (N)
- Into the page in the conductors on the right of the neutral plane

The resultant magnetic field of the armature appears as if a coil is situated on the neutral plane at a right angle to the main field. Applying the left-hand rule for a coil shows that a south pole exists at the top of the armature and a north pole at the bottom.

Comparing the field distributions shown in Figures 5 and 6, it can be seen that the magnetic fields at the upper tip of the north pole and the lower tip of the south pole are in the same direction. This strengthens the main field in these areas. The magnetic fields are in opposite directions at the lower tip of the north pole and the upper tip of the south pole. This weakens the main field in these areas.

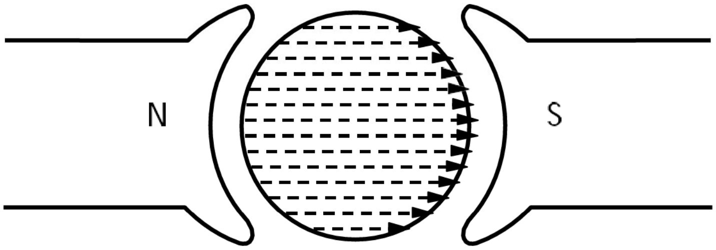


Figure 6 Main field flux

The original position of the neutral plane between the two field poles is called the *mechanical neutral plane*. In Figure 7, the distortion of the main field shows that the position at which conductors will not cut flux has shifted in the direction of rotation. The net effect is a shift in the position of the neutral plane. The shift is proportional to armature current. The shifted position at which the conductors do not cut flux is called the *electrical* or *magnetic neutral plane*.

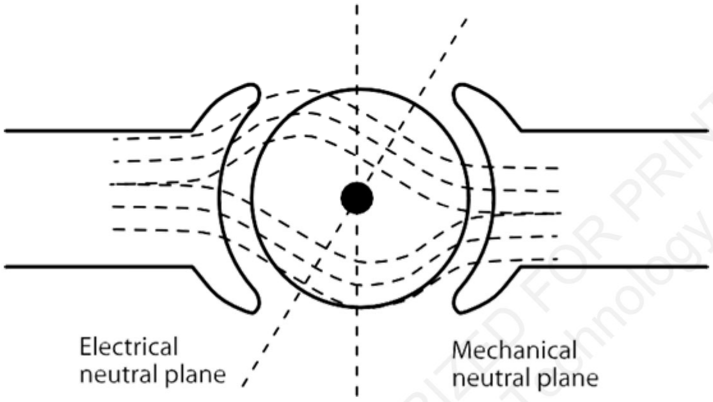


Figure 7 Main field distortion

Ideally, the brush position is set so that the armature coils will short as they cross the mechanical neutral plane. The shift of the electrical neutral plane with armature current causes an emf to be induced in coils crossing the mechanical neutral plane. High current flows in the shorted coils, limited only by the resistance of the coil and the brush. The result is excessive sparking at the contact point of the brush and the commutator.

Sparking can be eliminated if the position of the brushes is shifted in the direction of rotation, toward the electrical neutral plane. In early applications of DC generators, the brushes were mounted on rotational collars to enable an operator to shift the brushes in response to changing load conditions.

Interpoles

Brush shifting is a problem because electrical loads are rarely constant. This means that the brush position must be continually adjusted.

Armature reaction is caused by the magnetic field produced by armature current. Introducing additional fields to oppose the armature field can minimize distortion of the main field. This is done by positioning additional field poles on the mechanical neutral plane. These new poles are between the main poles, and are commonly called *interpoles*. Because they improve commutation, they are also called *commutating poles*. Figure 5 shows that a south interpole would be required at the top of the armature and a north interpole at the bottom. For generators, interpole polarity is the same as the main pole directly ahead in the direction of rotation.

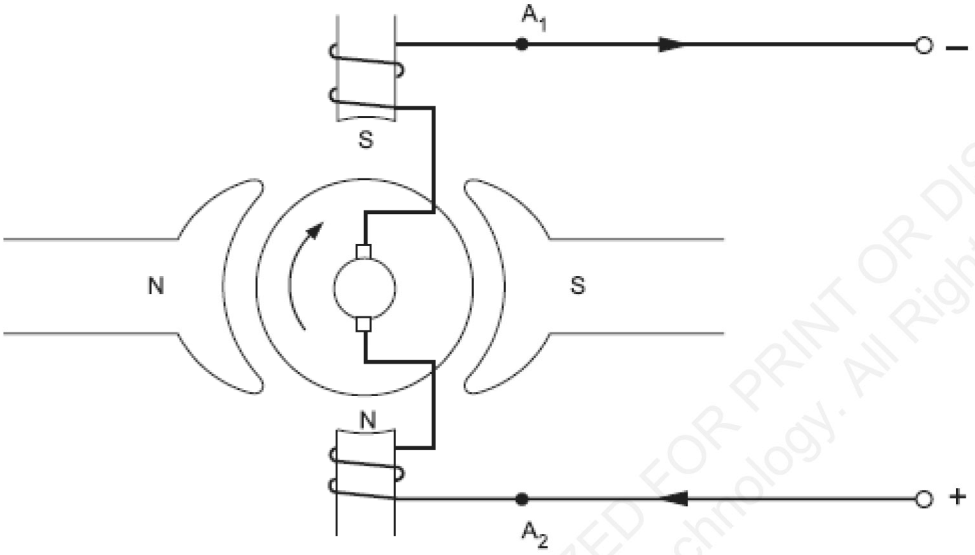


Figure 8 Interpole connection

The strength of the armature field depends on the armature current. The interpole winding is connected in series with the armature. Therefore, the strength of the interpole field also varies with armature current. To ensure correct polarity, the interpole is usually connected to the armature inside the machine. In Figure 8, the leads A_1 and A_2 include both the armature and the interpoles.

The desired effect of interpoles is concentrated at the mechanical neutral plane. Because of this and the limited physical space between the main poles, interpole field cores are very narrow.

Interpole windings consist of a few turns of large-gauge wire similar to series field windings.

Compensating windings

Interpoles do not eliminate all the field distortion caused by armature reaction. In large, high- performance DC generators, *compensating windings* (Figure 9) are placed in the main pole faces and connected in series with the armature to eliminate field distortion. Due to their high cost, compensating windings are far less common than interpoles.

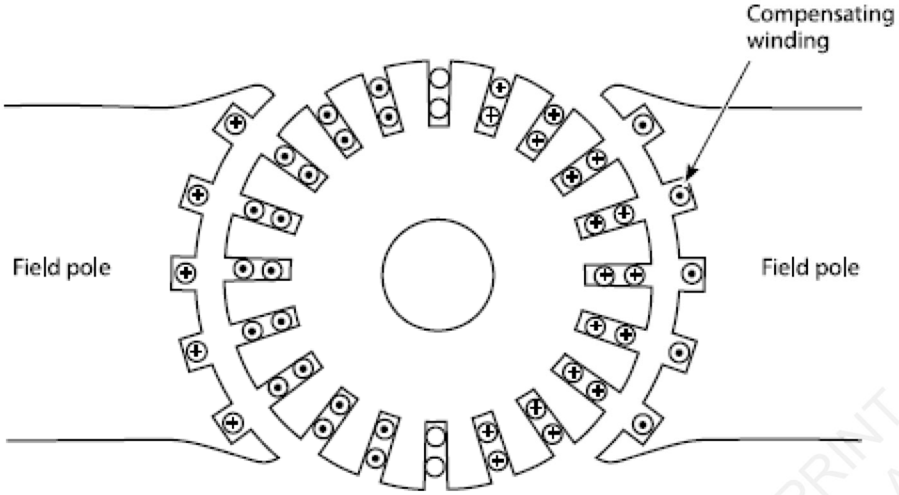


Figure 9 Compensating windings

Losses and efficiency

Energy that is drawn from the source but is not available at the output of the machine is considered lost. There are three types of power loss in DC generators: mechanical, electrical and magnetic (core).

Mechanical losses

Mechanical losses associated with rotation of the armature are commonly called *rotational losses*. These losses are due to bearing friction and the movement of air within the machine, called *windage losses*. Air movement is an important factor in preventing heat buildup within the machine.

Electrical losses

Electrical losses due to resistance occur whenever current flows in a conductor. Heat is produced that is proportional to the resistance times the square of the current (I^2R). Because the armature and series fields carry full load current, considerable heat is generated in the copper conductors.

Core losses

Core losses result from the action of magnetic fields on the materials in the magnetic paths through the machine. These paths include the frame, the field poles and the armature. Core losses include the heating effects of both hysteresis and eddy currents.

Calculating efficiency

For any device or machine, efficiency is defined as the ratio of the power out to the power in. Input power is always greater than output power because of various losses; therefore, this ratio is between 0 and 1. It is common to multiply the ratio by 100 and express efficiency as a percentage.

In the case of DC generators, the output power is the electrical power available at the output terminals. The input power is the mechanical energy drawn from the shaft rotation of the prime mover. Machine ratings always describe what is *available from* the machine. For example, a 100 kW DC generator can deliver 100 kW to an external electrical load. The additional power necessary to overcome the losses within the generator must also come from the prime mover, which must therefore deliver *more than* 100 kW. The efficiency of the prime mover is considered separately.

Example: A 100 kW DC generator is operating at full load. If the prime mover is delivering 125 kW to the shaft, determine the efficiency of the generator.

$$\begin{aligned}\text{Efficiency} &= \frac{\text{power out}}{\text{power in}} \times 100\% \\ &= \frac{100\ \text{kW}}{125\ \text{kW}} \times 100\% \\ &= 80\%\end{aligned}$$

☑ Now do Self-Test 2 and check the answers.

Self-Test 2

1. Small generators that use permanent magnets for field excitation are called _________ .
2. Describe the difference between separately excited and self-excited fields.
3. List the two ways in which field coils are connected in self-excited generators.
4. Which field windings are made of a low number of turns of large-gauge wire?
5. What device in the shunt field circuit is used to control generator voltage?
6. The buildup of voltage in a self-excited generator requires _________________________ .
7. List five factors that influence generated voltage.

8. Which of the factors listed in Question 7 can be varied in an operating generator?

9. What is the effect on generated voltage if the speed of the prime mover is decreased by one- third?

10. In a self-excited generator, voltage buildup requires the presence of ________________ .

11. Voltage buildup occurs until the generator reaches its ____________________________ .

12. Appropriate residual magnetism can be established on the field poles by a process commonly called ____ .

13. The value of field resistance that will limit field current to a value insufficient for voltage buildup is called ____ .

14. What should be done at generator start-up to avoid the problem described in Question 13?

15. Define *armature reaction*.

16. List two effects of armature reaction on the operation of a generator.

17. Interpole coils consist of a:
    a. large number of turns of small-gauge wire
    b. small number of turns of small-gauge wire
    c. large number of turns of large-gauge wire
    d. small number of turns of large-gauge wire

18. Interpole coils are connected:
    a. across the armature
    b. in series with the armature
    c. across the series field
    d. in series with the shunt field

19. The effects of armature reaction can also be minimized by placing windings called ________________________________ in the main pole faces.

20. List the three types of power loss in a generator.

21. Rotational losses include ________________ and _________________ .

22. How is the effect of eddy currents minimized in the construction of DC machines?

23. Heat produced by current flowing through the armature and field coils is called

______________________________________ .

24. Define *efficiency*.

25. A DC generator delivers 150 kW to a load at an efficiency of 75%. Determine the power delivered to the generator by the prime mover.

Chapter 3: Describe the characteristics of the various types of DC generators

There are three types of DC generators. Each type is categorized according to its field winding connections:

- The series generator (where the field windings are connected in series with the armature)
- The shunt generator (where the field windings are connected in parallel with the armature)
- The compound generator (where two sets of field windings are used—one in series, and one in parallel with the armature)

In order to obtain the desired performance, it is essential that the field coils be properly connected to the armature and to each other. To standardize and simplify this process, the National Equipment Manufacturers' Association (NEMA) developed a standard numbering system for lead identification.

The NEMA system uses the following letters to identify the leads of a DC machine:

- A for armature
- F for shunt field coils
- S for series field coils

Numerical subscripts are used to indicate current direction in the windings. Electrons normally flow through the field windings from even- to odd-numbered subscripts (that is, from F_2 to F_1 and from S_2 to S_1).

Throughout this book and the next, the following convention will be used:

- For clockwise rotation observed from the non-drive end of the machine, A_1 will be negative.
- Since the armature is a voltage source, electrons will flow through the armature internally from A_2 to A_1, making A_1 negative with respect to A_2 for the external circuit.

In most DC generators, the drive end is at the opposite end to the commutator and is mechanically coupled to the prime mover. This mechanical arrangement facilitates maintenance of the commutator and brushes.

Shunt generator

The schematic in Figure 1 shows the shunt field connected in parallel with the armature, hence the term *shunt*. It is common to include a rheostat in the field circuit to control the no load terminal voltage.

In this schematic:

- Electron flow through the armature (the voltage source) is from A_2 to A_1.
- Electron flow through the shunt field (which is a load across the armature) is from F_2 to F_1.

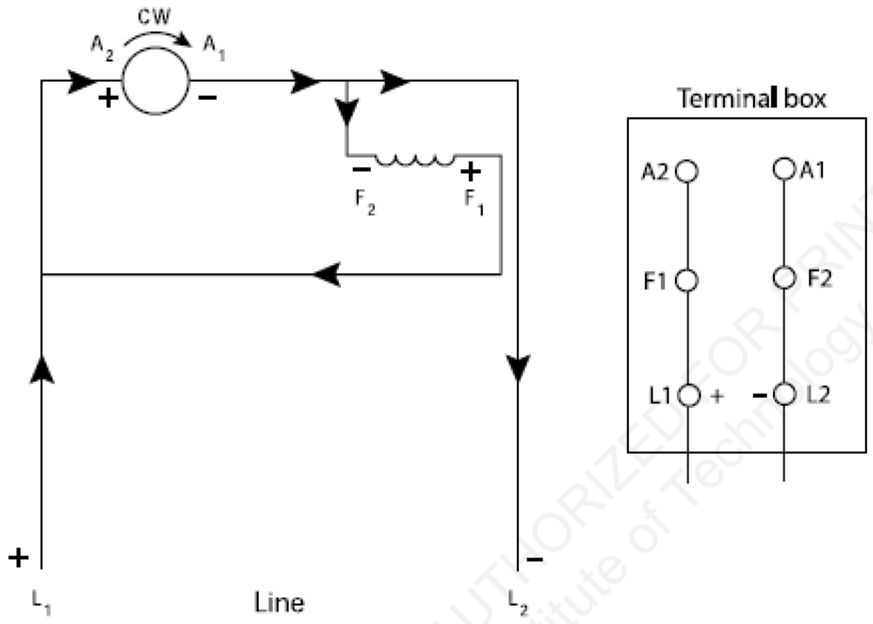


Figure 1 Shunt generator

If the polarity of the residual magnetism is reversed by re-flashing the field, the voltage will build up with opposite polarity and A_1 will now be positive.

When a shunt generator is operating at no load, the generated voltage (Eg) appears across the line terminals, L_1 and L_2. When an external load is connected across the output terminals, current flows through the armature. Its value is determined by the impedance of the load.

Three factors associated with armature current can cause a reduction in terminal voltage with the load:

- Although the resistance of the armature is very low (in the order of a few ohms), current through the armature results in an internal voltage drop. This internal voltage drop (often called the *IR drop* of the armature) results in a slightly lower terminal voltage.

- With any increase in load current, the field-weakening effects of armature reaction also increase. This results in a lower generated voltage.

- Since the shunt field is connected across the armature, any reduction in armature voltage will result in a lower field current and a corresponding reduction in field strength. This results in a further reduction of generated voltage. (Separately excited generators are not affected by this third factor.)

Figure 2 shows the reduction in terminal voltage as load current increases in a typical shunt generator.

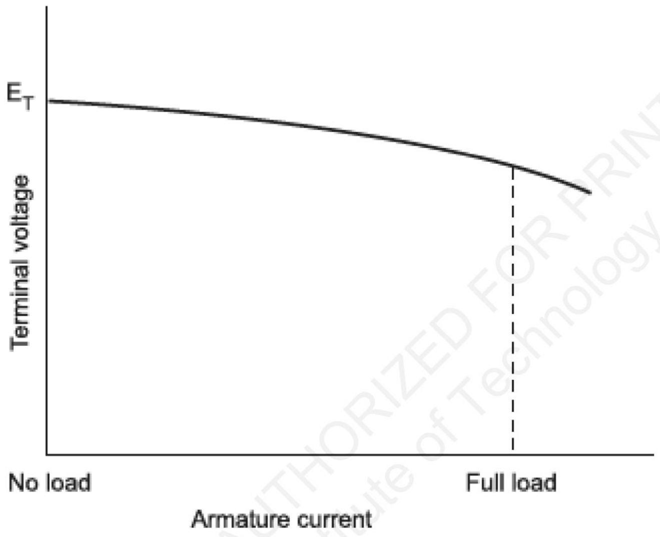


Figure 2 Shunt generator characteristic curve

The change in terminal voltage from no load to full load is called *voltage regulation*. It is commonly expressed as a percentage. It is calculated using the following formula:

$$\%\ \text{voltage regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

Series generator

As seen from its voltage characteristics, the series generator is not a practical machine. However, knowing the characteristics of series field coils is important to understand the compound generator, which will be described later.

As previously discussed, A_1 and A_2 indicate the armature leads, and S_1 and S_2 indicate the leads of the series field coils. For clockwise rotation, A_1 is negative and current flows through the series field from S_2 to S_1.

Note that a load must be connected across the line terminals of a series generator in order to allow field current. Otherwise, the field circuit is "open."

Figure 3 shows the series field connected to the armature circuit.

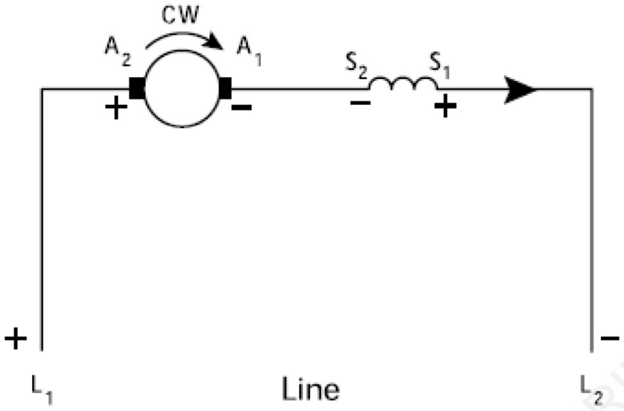


Figure 3 Series field connected to armature circuit

With armature lead A_1 connected to field lead S_2, electrons flow internally from A_2 to A_1 and from S_2 to S_1.

Figure 4 shows the effect of connected load on terminal voltage. Without an external load, armature current is zero and no current flows through the series field. The only source of excitation is residual magnetism, so the no-load terminal voltage is extremely low. As resistance of the external load is decreased, armature current increases and thereby increases the strength of the series field. Since generated voltage is proportional to speed and flux, the terminal voltage rises steeply as a function of load current. Applications for a generator having this voltage characteristic are extremely limited.

The rise in generated voltage with increasing armature current can be useful, however, in offsetting the decrease in terminal voltage associated with the shunt generator. The compound generator uses the voltage characteristics of both series and shunt fields.

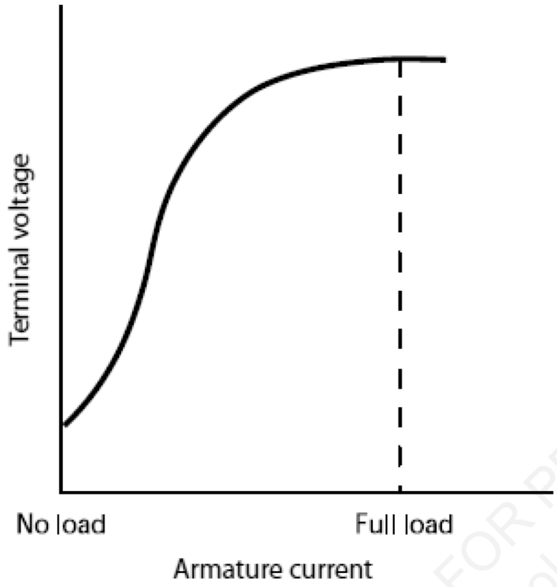


Figure 4 Effect of connected load on terminal voltage

Compound generator

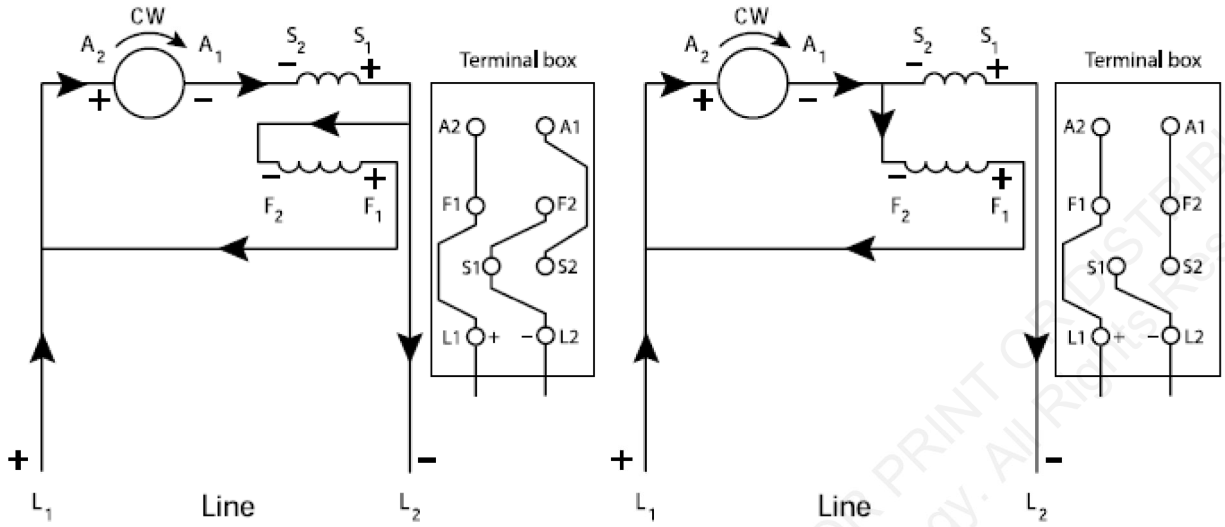
The compound generator contains both shunt and series field coils placed on the same field core. Incorrect connection of the field winding terminals will have a serious effect on the performance characteristics of the machine. For example, current flowing from F_2 to F_1 in the shunt coils and from S_2 to S_1 in the series coils will produce magnetic fields that add a condition called *cumulative compound*. If, however, the connection of the series field is reversed, causing current to flow from S_1 to S_2, the resulting fields would oppose or subtract. This latter connection is called *differential compound*.

When connecting and operating compound generators, the shunt field should be considered the main field, with the series field either aiding or opposing (bucking) the magnetic polarity of the shunt field.

There are two possible ways to connect the shunt field coils to the armature, *long shunt* and *short shunt*:

- In long shunt, the shunt field is connected across the series combination of both the armature and series field, that is, across the line.
- In short shunt, the shunt field is connected across the armature only.

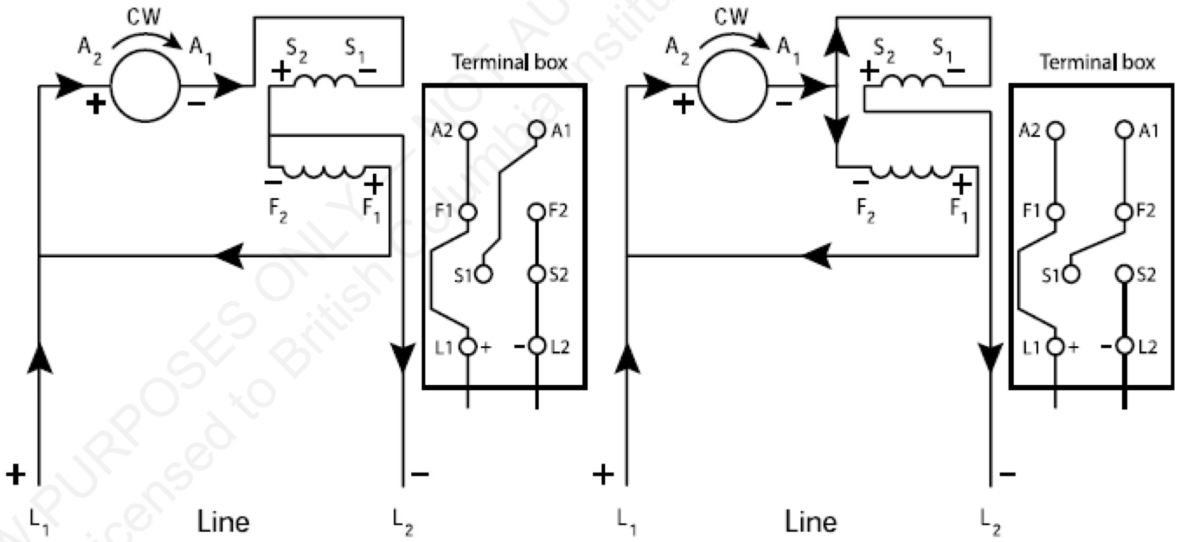
Figures 5 and 6 show long and short shunt connections for cumulative and differential compound DC generators. When studying these figures, note the direction of the current in the series field with respect to the shunt field.


CW
A2
A1
S2
S1
F2
F1
Terminal box
A2
A1
F1
F2
S1
S2
L1
L2
+
−
L1
Line
L2

Long shunt

Short shunt

Figure 5 Cumulative compound generator


CW
A2
A1
S2
S1
F2
F1
Terminal box
A2
A1
F1
F2
S1
S2
L1
L2
+
−
L1
Line
L2

Long shunt

Short shunt

Figure 6 Differential compound generator

Cumulative compound

The cumulative compound connection is far more common in practical application than the differential compound. The degree to which the series field aids the shunt field is an important consideration in designing the generator for a specific application. Three variations are possible:

Flat-compound

The increasing flux produced by armature current flowing in the series winding offsets the drooping voltage characteristic associated with the shunt winding. The result is that the terminal voltage is relatively flat or constant with respect to load current.

Over-compound

Adding additional turns on the series field provides a rising voltage characteristic that is useful in supplying DC loads at the end of a long transmission line. The rise in voltage at the terminals of the generator compensates for the line drop to the load.

Under-compound

Decreasing the number of series field turns results in a voltage characteristic that lies somewhere between the flat-compound and the shunt generator.

In Figure 7, the field rheostat is used to adjust the no-load voltage of the generator and a diverter rheostat is used to control the compounding and adjust the full-load voltage of the generator.

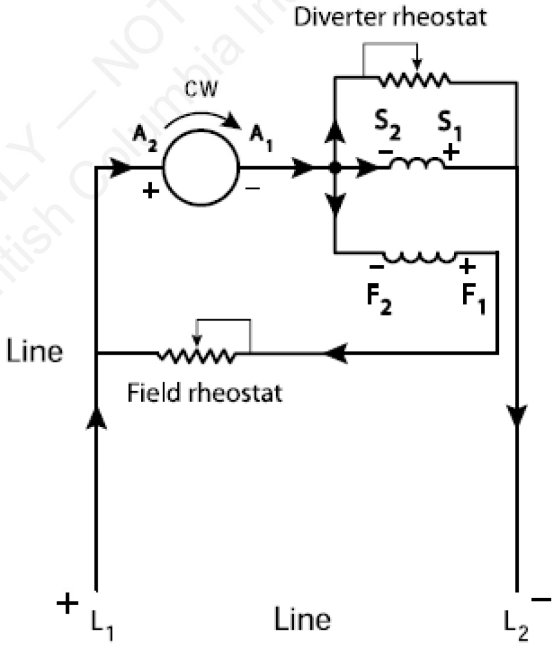


Figure 7 Diverter and field rheostats

Differential compound

To appreciate the strange characteristic curve of the differential generator, it is important to recall that the shunt field is the main source of excitation. The effect of the series field becomes more pronounced with increasing armature current. The “droop” in the voltage characteristic (Figure 8) is more severe than that of the shunt generator. As armature current increases, a point is reached where the series winding flux begins to overpower the shunt winding flux, causing a rapid decrease in terminal voltage.

The main application for the differential compound generators is DC arc welding. To start the arc, a high voltage is required to overcome contact resistance. A much lower voltage is then required to maintain the arc.

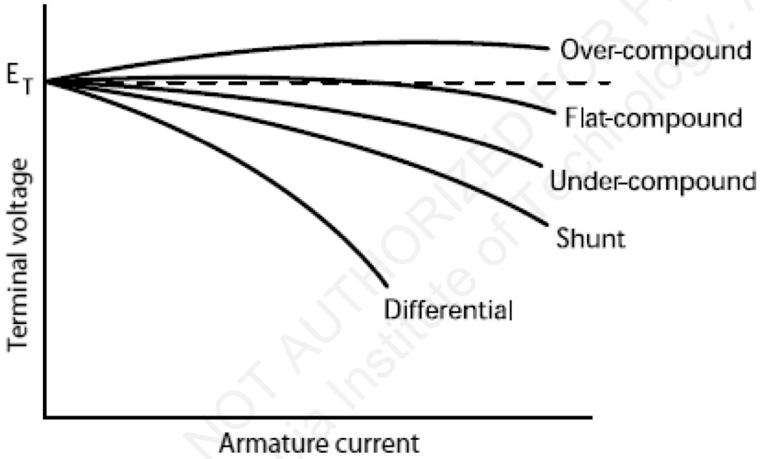


Figure 8 Characteristic curves for DC generators

The effect of long shunt versus short shunt on terminal voltage is relatively minor. However, for maximum shunt field excitation when connecting DC generators (or motors), a general rule is to connect the shunt field across the source of emf. For a generator, this would be the short shunt connection, since the armature is the source of emf. In this case, the IR drop of the series field has no effect on shunt field current.

☑ Now do Self-Test 3 and check the answers.

Self-Test 3

1. A generator characteristic curve shows the effect of ____________________ on ____________________.

2. Describe the conditions that must be satisfied to obtain the desired performance when connecting a generator.

3. List the letters that are used in the NEMA system to identify the armature, shunt field and series field.

4. The terminal voltage of a shunt generator is controlled by ____________________ .

5. What determines the amount of current that flows through an armature?

6. List the factors that cause a reduction in terminal voltage with increasing load.

   ____

   ____

   ____

7. Is the series generator a practical machine?

8. Why would it not be practical to control the output of a series generator with a field rheostat?

9. Why is the no-load voltage of a series generator extremely low?

10. In a series generator, why does the terminal voltage rise with increasing load?

11. Describe how the voltage characteristic of series field coils could be useful.

12. A compound generator contains both ____________________ and __________________ fields.

13. The condition under which the series field adds to the shunt field is called _________________ .

14. The condition under which the magnetic flux of the series and shunt fields oppose each other is called ____ .

15. Describe the difference between long shunt and short shunt connections.

16. A compound generator that has a relatively constant terminal voltage characteristic is called ______________________________ .

17. Line drop can be compensated for by using a generator that is ________________ .

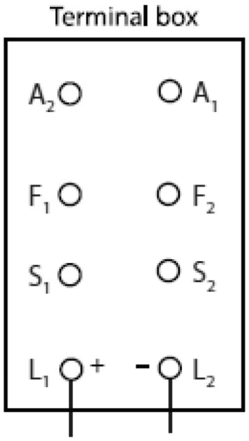
18. Which of the following generators has the most severe drop in terminal voltage with load?
    a. series
    b. shunt
    c. cumulative compound
    d. differential compound

19. Which generator would be the most suitable for arc welding?
    a. series
    b. shunt
    c. cumulative compound
    d. differential compound

20. With respect to long versus short shunt connections, what is a general rule?

21. Draw the connection diagram for a cumulative compound short shunt DC generator with diverter rheostat and field rheostat. The prime mover is turning the generator in a clockwise direction. Label all components according to NEMA standards. Show direction of currents and indicate line polarity.

22. Connect the terminal box shown as a cumulatively compounded, short-shunt generator driven in a CW direction by the prime mover.



Answer Key

Self-Test 1

1. the type of enclosure
2. armature
3. frog leg, lap and wave
4. lap winding
5. to maintain the current in one direction to the external circuit
6. carbon, electro-graphite, graphite, copper graphite
7. 1, 2
8. Field poles provide the necessary magnetic field.
9. sleeve, ball
10. open

Self-Test 2

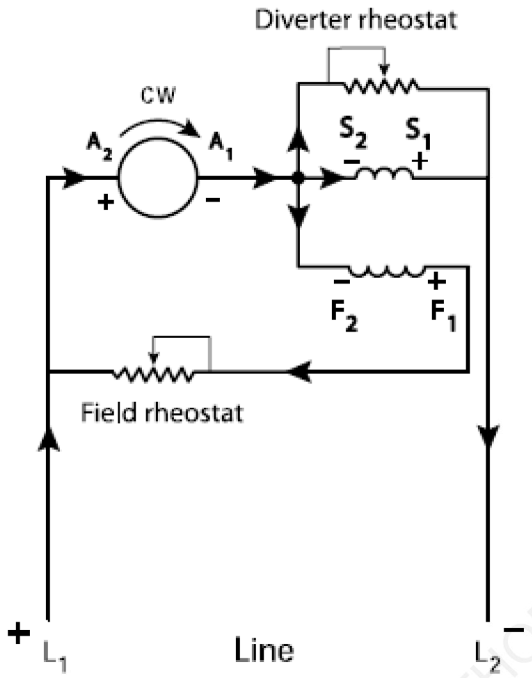
1. magnetos
2. The current for separately excited fields is obtained from a source external to the machine.
3. series and parallel (shunt)
4. series windings
5. rheostat
6. residual magnetism
7. number of poles, flux per pole, rotational speed, number of armature paths, number of active armature conductors
8. flux per pole (excitation) and rotational speed
9. Generated voltage is reduced by one third.
10. residual magnetism
11. no-load terminal voltage
12. flashing the field
13. critical field resistance
14. Field rheostats should be set to their minimum ohmic value.
15. Armature reaction is a distortion of the main field flux caused by current flowing in armature conductors.
16.
    - A reduction in terminal voltage with increasing load
    - Impaired commutation
17. d. small number of turns of large-gauge wire
18. b. in series with the armature
19. compensating windings
20. mechanical, electrical, magnetic
21. bearing friction, windage
22. by laminating the core materials

23. copper losses
24. Efficiency is the ratio of power out to power in.
25. 200 kW

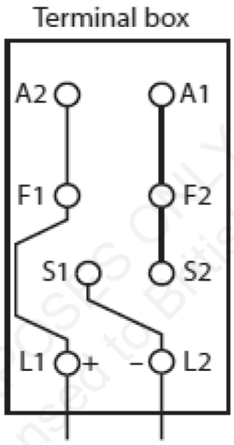
Self-Test 3

1. connected load, terminal voltage
2. The field coils must be properly connected with respect to the armature and to each other.
3. armature = A; shunt field = F; series field = S
4. a rheostat in the field circuit
5. the impedance of the connected load
6. IR drop of the armature, armature reaction and loss of field current due to a reduction in generated voltage
7. no
8. The rheostat would have to carry the high armature current, resulting in high wattage losses.
9. In the absence of a connected load (open circuit), no current flows through the series field coils.
10. As armature current increases, the strength of the series field increases.
11. The rising voltage characteristic is used to offset the decrease in terminal voltage associated with shunt field excitation in a compound generator.
12. series, shunt
13. cumulative compound
14. differential compound
15. In long shunt, the shunt field is connected across the line. In short shunt, the shunt field is connected across the armature.
16. flat-compound
17. over-compound
18. d. differential compound
19. d. differential compound
20. Connect the shunt field across the source of emf.

21.


Diverter rheostat
CW
A_2
A_1
+
–
S_2
S_1
–
+
–
+
F_2
F_1
Field rheostat
+
L_1
Line
L_2
–

22.


Terminal box
A2
A1
F1
F2
S1
S2
L1
+
–
L2

ELECTRICAL TRADES APPRENTICESHIP PROGRAM

MAINTAIN DC GENERATING SYSTEMS

Level 3

MAINTAIN DC GENERATING SYSTEMS

Chapter 1: Describe basic troubleshooting and maintenance for DC generators................2
Self-Test 1..9
Answer Key..11

Chapter 1: Describe basic troubleshooting and maintenance for DC generators

Operational difficulties with DC generators are due to either electrical faults or mechanical faults. With this in mind, this Learning Task introduces the basic procedures for troubleshooting and maintaining DC generators.

Electrical faults

In general, electrical faults in DC generators result from open circuits, short circuits, ground faults, or incorrect connections.

For their proper operation, keep generators clean and dry. Keep in mind that because most generators are open machines, their armature windings require cleaning on a routine basis. It is also important to conduct insulation tests on these windings regularly.

Perform the following tests if a DC generator is not performing as it should:

1. Confirm that the generator's armature is rotating in the correct direction.
2. Ensure that the field resistance is set to zero, or as close to zero as possible.
3. Confirm that the armature and field coils are connected correctly and securely.
4. Confirm that the field coils and armature windings are closed circuits. Do this by performing continuity tests on each.
5. Confirm that there are no ground faults in any of the generator's circuits.
6. Using an insulation tester (i.e., a megger), confirm that the insulation of the armature windings is undamaged.

Testing the armature for electrical faults

Most electrical faults in DC machines occur in their armature windings. To test the armature for electrical faults, it must first be removed from the machine. Once removed, perform the following tests to identify which type of electrical fault has occurred in the armature.

Testing for an armature faulting to ground

Connect a 120 V supply and a test lamp between any commutator bar and the shaft. If the test lamp lights, the armature windings are in contact with ground. This fault is commonly known as a grounded coil.

Testing for an open armature circuit

The open armature circuit tests for frog-leg and wave-type windings vary and are therefore not addressed here. For lap-wound armatures, apply a low value of voltage to two bars on opposite sides of the commutator. As the leads of the voltmeter are moved around the commutator measuring the voltage between adjacent bars, equal voltages should be observed. In the event of an open coil or bar, the full applied voltage will be observed between the bars connected to the faulty coil. This fault is commonly known as an open coil.

A DC generator is driven by its prime mover; as such, it will not experience difficulties reaching nameplate speed if it has an open armature circuit, which is a common indicator of open armature circuits in DC motors. Additionally, and again unlike DC motors, DC generators with open armature circuits may not spark excessively at their brushes and they may not have burn marks on their commutators.

Testing for a shorted armature circuit

A growler (see Figure 1) is required for this test. A growler is a device that produces a strong alternating magnetic field. A strong alternating magnetic field will induce a relatively strong alternating voltage into any conductor through which it passes. If that conductor forms a closed loop with relatively low resistance, which a short circuit exemplifies, the induced alternating voltage will result in an intense alternating current passing through the conductor. This alternating current produces a strong alternating magnetic field that surrounds the conductor. A piece of steel placed near the conductor will experience an attraction to it that varies in strength relative to the frequency and intensity of magnetic field surrounding the conductor.

To perform the test, first place the armature on the energized growler. Next, place a steel strip, such as a hacksaw blade, on top of the armature and along its axis. Now slowly rotate the armature. The steel strip will vibrate excessively when a slot containing a shorted armature winding is directly beneath it. This fault is commonly known as a shorted coil.

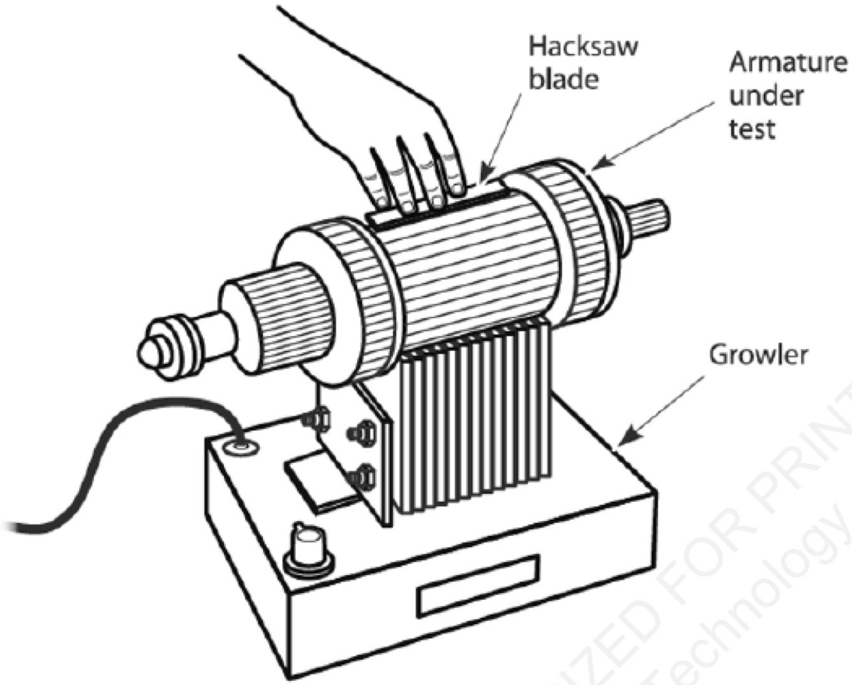


Figure 1 Using a growler to test for shorted coils

Brush/commutator maintenance

When operated correctly, a DC generator should not overheat or spark excessively at the brushes.

Brushes

Brushes must be constantly checked during operation. Pay special attention to the following:

- Make sure all brushes are of the same type and grade.
- Make sure all brushes are of the same length, neither too short nor too long, to allow free movement in the brush holder.
- Check for free movement of brushes in the holder. Any rough particles in the face should be removed and the brush reseated.
- Check for suitable pressure against the commutator surface (usually between 1 and 2 psi).
- Seat the brushes by using sandpaper placed between the commutator surface and the brushes, with the rough side against the brush contact surface. Do not use emery cloth, as it will release a conductive grit that may become lodged between commutator segments, resulting in their shorting out.

- Repairing commutators is costly and requires that the machine be taken out of service. Brush replacement is quick and relatively inexpensive. Replace brushes regularly!

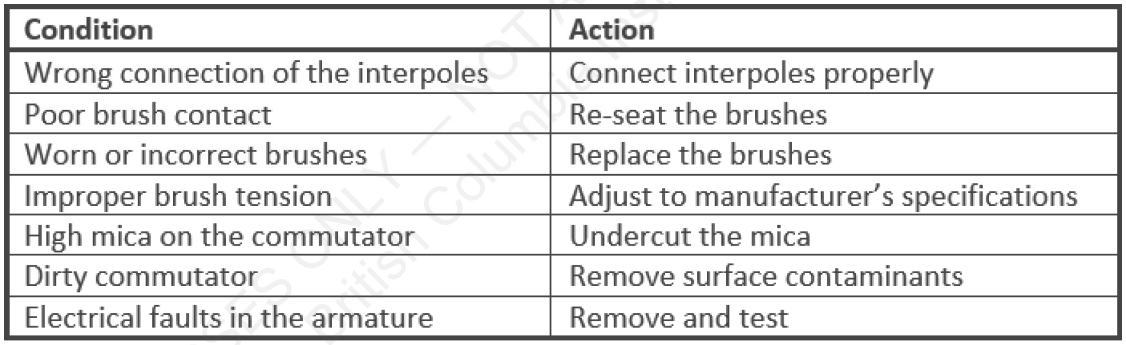
Commutator

The condition of the commutator is fundamental for the performance of DC generators. This means that the commutator must be checked regularly. Look for the following:

- The commutator must be kept free of oil and grease and the slots between the bars must be kept clean.
- Under normal operation condition, the film on the surface of the commutator will be a glossy, dark brown or slightly black colour.
- A polished copper surface, or surface wear, indicates that the brushes must be replaced.
- A black and thick colouring, which usually occurs due to long overloads with humidity, indicates that there is excessive patina on the commutator. Do not use emery cloth to remove the patina. Instead, use sandpaper or an appropriate milling wheel.

Excessive brush sparking may result from any of the conditions listed in Table 1.

Table 1 Brush/commutator maintenance



Condition	Action
Wrong connection of the interpoles	Connect interpoles properly
Poor brush contact	Re-seat the brushes
Worn or incorrect brushes	Replace the brushes
Improper brush tension	Adjust to manufacturer's specifications
High mica on the commutator	Undercut the mica
Dirty commutator	Remove surface contaminants
Electrical faults in the armature	Remove and test

Mechanical faults

Mechanical faults can result in overheating and/or excessive vibration. Common mechanical faults include the following:

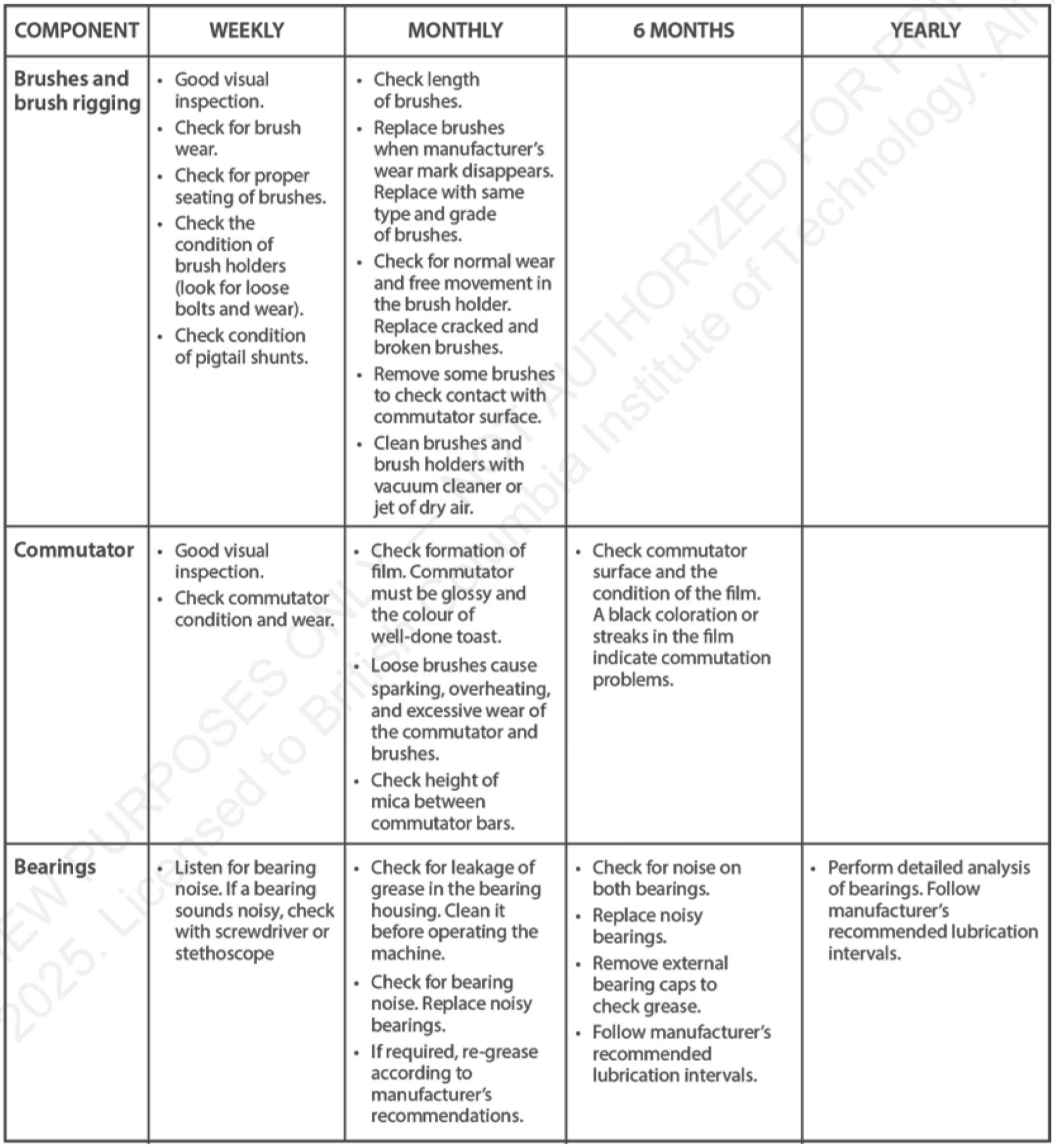
- worn bearings
- armature imbalance
- improper alignment of the generator and the prime mover
- loose coupling between the generator and prime mover
- loose mounting bolts

Regular maintenance includes cleaning, lubricating, and routine inspection of the mechanical condition of the generator and the prime mover.

Shaft alignments

Proper alignment of a generator's shaft with its prime mover is critical for minimizing vibration and extending bearing life. An armature shaft that moves up and down freely indicates worn bearings. Check alignment using devices designed for the purpose, specifically dial indicators and laser aligners. Typically, a generator and its prime mover undergo alignment during commissioning, after which their alignment is unlikely to change.

Table 2 Maintenance Schedule



COMPONENT	WEEKLY	MONTHLY	6 MONTHS	YEARLY
Brushes and brush rigging	• Good visual inspection. • Check for brush wear. • Check for proper seating of brushes. • Check the condition of brush holders (look for loose bolts and wear). • Check condition of pigtail shunts.	• Check length of brushes. • Replace brushes when manufacturer's wear mark disappears. Replace with same type and grade of brushes. • Check for normal wear and free movement in the brush holder. Replace cracked and broken brushes. • Remove some brushes to check contact with commutator surface. • Clean brushes and brush holders with vacuum cleaner or jet of dry air.		
Commutator	• Good visual inspection. • Check commutator condition and wear.	• Check formation of film. Commutator must be glossy and the colour of well-done toast. • Loose brushes cause sparking, overheating, and excessive wear of the commutator and brushes. • Check height of mica between commutator bars.	• Check commutator surface and the condition of the film. A black coloration or streaks in the film indicate commutation problems.	
Bearings	• Listen for bearing noise. If a bearing sounds noisy, check with screwdriver or stethoscope	• Check for leakage of grease in the bearing housing. Clean it before operating the machine. • Check for bearing noise. Replace noisy bearings. • If required, re-grease according to manufacturer's recommendations.	• Check for noise on both bearings. • Replace noisy bearings. • Remove external bearing caps to check grease. • Follow manufacturer's recommended lubrication intervals.	• Perform detailed analysis of bearings. Follow manufacturer's recommended lubrication intervals.

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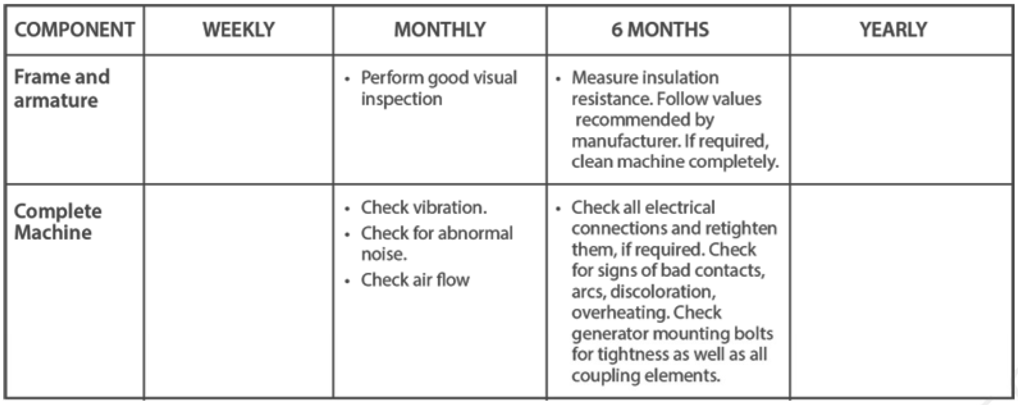
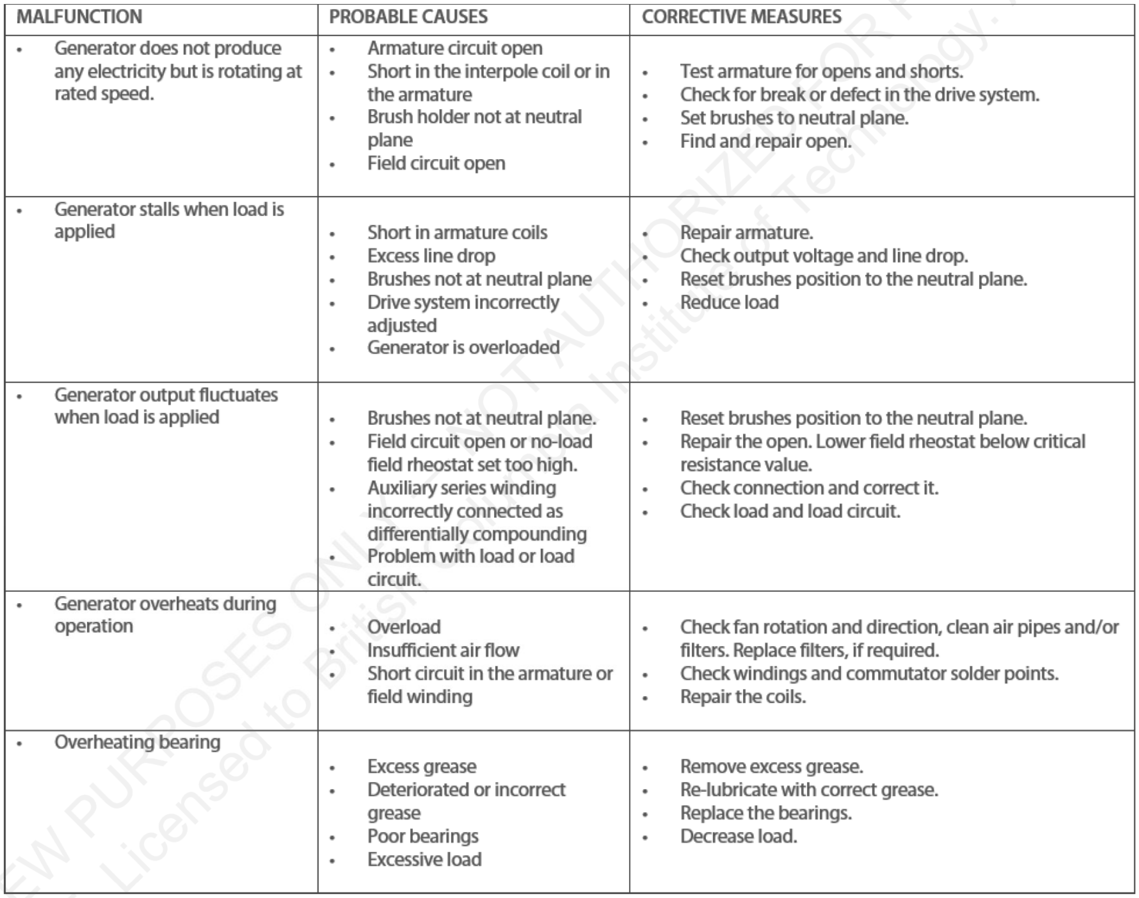
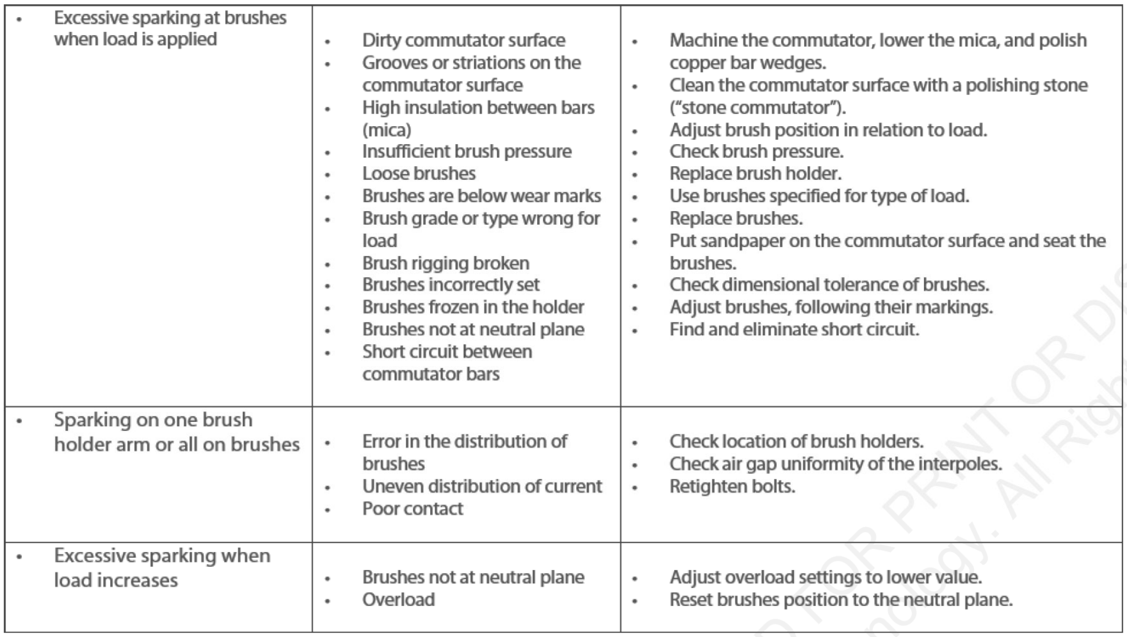


COMPONENT	WEEKLY	MONTHLY	6 MONTHS	YEARLY
Frame and armature		- Perform good visual inspection	- Measure insulation resistance. Follow values recommended by manufacturer. If required, clean machine completely.	
Complete Machine		- Check vibration. - Check for abnormal noise. - Check air flow	- Check all electrical connections and retighten them, if required. Check for signs of bad contacts, arcs, discoloration, overheating. Check generator mounting bolts for tightness as well as all coupling elements.	

Table 3 Troubleshooting



MALFUNCTION	PROBABLE CAUSES	CORRECTIVE MEASURES
• Generator does not produce any electricity but is rotating at rated speed.	• Armature circuit open • Short in the interpole coil or in the armature • Brush holder not at neutral plane • Field circuit open	• Test armature for opens and shorts. • Check for break or defect in the drive system. • Set brushes to neutral plane. • Find and repair open.
• Generator stalls when load is applied	• Short in armature coils • Excess line drop • Brushes not at neutral plane • Drive system incorrectly adjusted • Generator is overloaded	• Repair armature. • Check output voltage and line drop. • Reset brushes position to the neutral plane. • Reduce load
• Generator output fluctuates when load is applied	• Brushes not at neutral plane. • Field circuit open or no-load field rheostat set too high. • Auxiliary series winding incorrectly connected as differentially compounding • Problem with load or load circuit.	• Reset brushes position to the neutral plane. • Repair the open. Lower field rheostat below critical resistance value. • Check connection and correct it. • Check load and load circuit.
• Generator overheats during operation	• Overload • Insufficient air flow • Short circuit in the armature or field winding	• Check fan rotation and direction, clean air pipes and/or filters. Replace filters, if required. • Check windings and commutator solder points. • Repair the coils.
• Overheating bearing	• Excess grease • Deteriorated or incorrect grease • Poor bearings • Excessive load	• Remove excess grease. • Re-lubricate with correct grease. • Replace the bearings. • Decrease load.



• Excessive sparking at brushes when load is applied	• Dirty commutator surface • Grooves or striations on the commutator surface • High insulation between bars (mica) • Insufficient brush pressure • Loose brushes • Brushes are below wear marks • Brush grade or type wrong for load • Brush rigging broken • Brushes incorrectly set • Brushes frozen in the holder • Brushes not at neutral plane • Short circuit between commutator bars	• Machine the commutator, lower the mica, and polish copper bar wedges. • Clean the commutator surface with a polishing stone ("stone commutator"). • Adjust brush position in relation to load. • Check brush pressure. • Replace brush holder. • Use brushes specified for type of load. • Replace brushes. • Put sandpaper on the commutator surface and seat the brushes. • Check dimensional tolerance of brushes. • Adjust brushes, following their markings. • Find and eliminate short circuit.
• Sparking on one brush holder arm or all on brushes	• Error in the distribution of brushes • Uneven distribution of current • Poor contact	• Check location of brush holders. • Check air gap uniformity of the interpoles. • Retighten bolts.
• Excessive sparking when load increases	• Brushes not at neutral plane • Overload	• Adjust overload settings to lower value. • Reset brushes position to the neutral plane.

Table 3 lists the common characteristics of a malfunctioning DC generator, the probable cause and corrective measures for each situation.

☑ Now do Self-Test 1 and check the answers.

Self-Test 1

1. When a DC generator is operating correctly, what should not occur at its brushes?

2. Electrical faults in DC generators typically result from which four conditions?

3. Continuity tests of the armature and field circuits are typically used to locate which types of faults?

4. Which of the following test equipment is most effective in conducting insulation tests?
   a. ohmmeter
   b. Wheatstone bridge
   c. megohmmeter
   d. continuity tester

5. What is the name of the device often used to test for shorted armature windings?

6. List three common mechanical faults of DC generators.

7. What condition is indicated by an armature shaft that moves up and down freely?

8. What are the names of the two devices commonly used to detect improper alignment of a generator and prime mover.

9. List five conditions that will cause the brushes of a DC generator to spark excessively.

Answer Key

Self-Test 1

1. Excessive sparking
2. Open circuits, short circuits, ground faults, or incorrect connections.
3. Open circuits
4. c. Megohmeter
5. Growler
6. Worn bearings, unbalanced armature, improper alignment, loose coupling, loose mounting bolts
7. Worn bearings
8. Dial indicator, laser aligner
9. Wrong interpole polarity, poor brush contact, worn brushes, improper brush tension, high mica, dirty commutator, armature faults

ELECTRICAL TRADES APPRENTICESHIP PROGRAM

INSTALL DC MOTORS

Level 3

INSTALL DC MOTORS

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Answer Key 42

Chapter 1: Describe the operating principles of DC motors

Whenever a conductor carries current in the presence of a magnetic field, a force will act on the conductor at a right angle to the field. This principle of magnetism is called the *motor effect*.

Figure 1 shows a single conductor between two field poles and the resulting magnetic field.

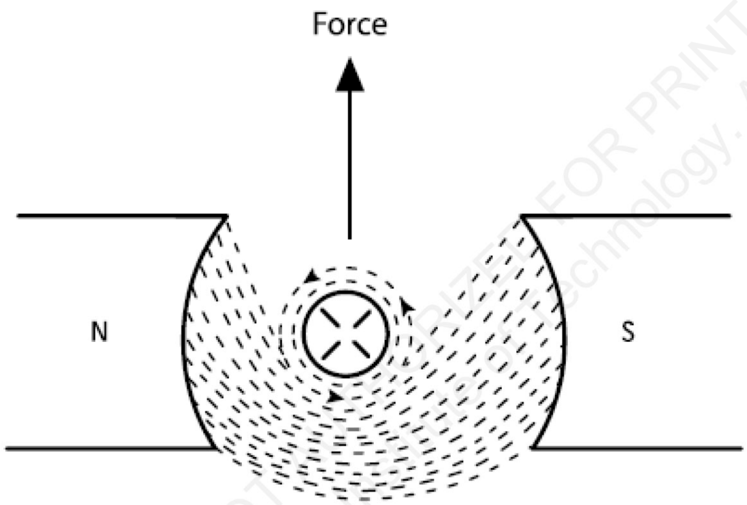


Figure 1 Motor effect

For the current direction shown, the flux above the conductor opposes or cancels the main field. Below the conductor, the fields are in the same direction and reinforce the main field. Magnetic lines in the same direction repel, and an upward force is exerted on the conductor. Note that the electron flow convention for current is used throughout this Learning Guide.

Right-hand motor rule

The right-hand motor rule provides a simple way to determine the direction of force acting on a conductor within a magnetic field. See Figure 2.

1. Point the first finger of the right hand in the direction of the magnetic flux of the field.
2. Point the middle finger in the direction of electron current flow.
3. The thumb now points in the direction of the force exerted on the conductor.

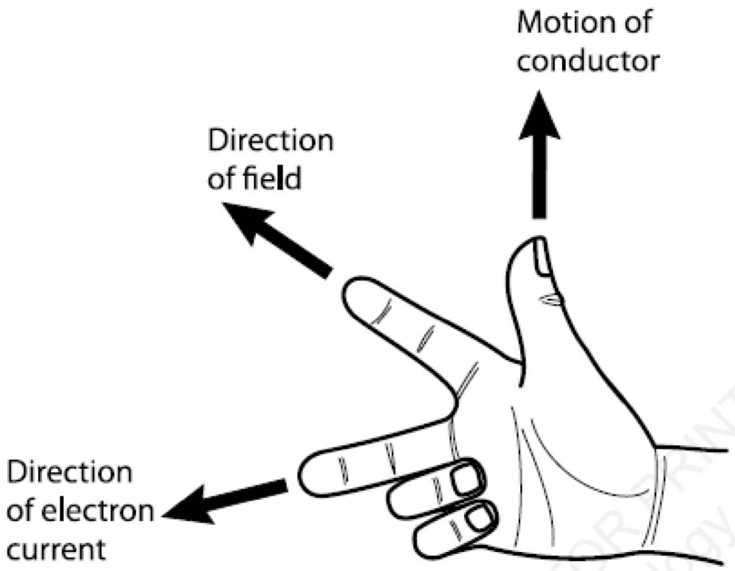

Motion of conductor
Direction of field
Direction of electron current

Figure 2 Right-hand motor rule

Neutral plane

As discussed earlier with DC generators, brushes are positioned to short circuit the armature coils as they cross the neutral plane (Figure 3).

The force acting on the conductor as it crosses the neutral plane is zero. If the right- hand motor rule to the armature conductors shown in Figure 3 is applied, the fact that the forces act in opposite directions on each side of the neutral plane will be seen. However, with respect to the centre of the armature, all forces act to produce clockwise rotation.

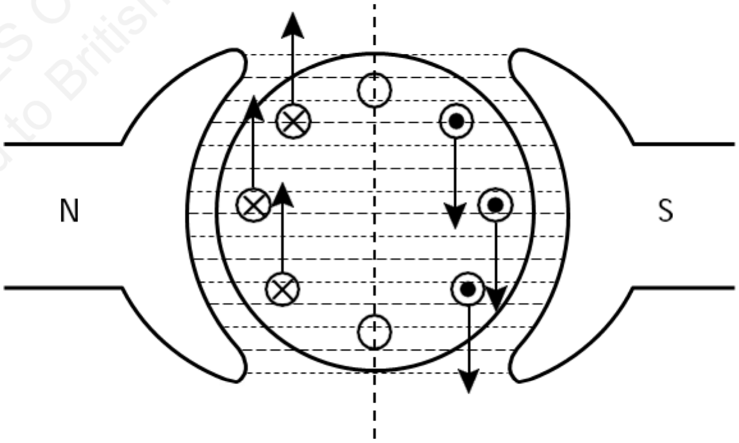


Figure 3 Neutral plane

Commutator action

The main difference between DC motors and generators lies in the operation of the armature. For the generator, the armature is a source of emf that delivers current to a load. For the motor, the armature is a load that draws current from an external source. Figure 4 shows a generator and a motor that both rotate in the same direction. Notice that the direction of the motor armature current is opposite to the direction of the current in the generator.

In a generator, the commutator and brushes keep the current flowing in one direction with respect to an external load. In a motor, the direction of thrust caused by the motor effect must change as the coils cross the neutral plane. To do this the commutator ensures that the current in each armature coil changes direction as the coil crosses the neutral plane.

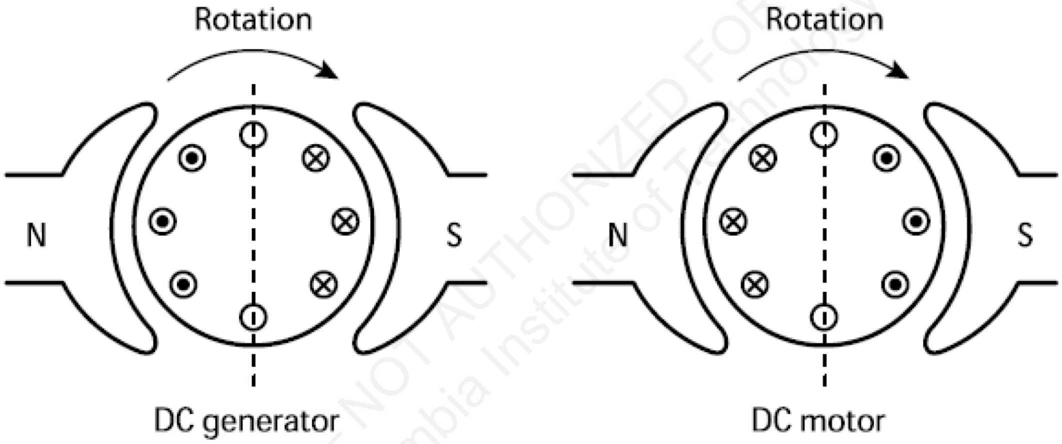


Figure 4 Armature current

Reversing rotation

According to the right-hand motor rule, the direction of the force acting on a conductor is a function of the direction of the magnetic flux and the direction of current in the armature. The direction of rotation can be changed by doing one of the following:

- Reversing the direction of the armature current by reversing the connection of the armature leads (A1 and A2)
- Reversing the magnetic polarity of the field poles by reversing the connection of both the series field (S1 and S2) and the shunt field (F1 and F2)

Torque

Torque is defined as a twisting or turning force that is capable of producing rotation about an axis. In a motor, torque results from forces acting on current-carrying armature conductors. The force on each armature conductor results from the interaction between the main magnetic field and the field produced by current flowing in the armature.

The following formula shows that torque is directly proportional to the product of flux and armature current:

$$T = k\Phi I$$

where:

T = torque in newton-metres

Φ = flux (excitation) in webers

I = armature current in amperes

k = constant of proportionality that includes factors such as:

- The number of poles
- The number of paths
- The total number of conductors on the armature

When studying motors, it is important to understand that the torque developed by a motor is determined by the mechanical load. At no load, the motor will draw sufficient current to overcome the losses of the machine.

Action of counter emf

Faraday's law of electromagnetic induction is based on the principle that when a conductor is moved within a magnetic field, a voltage is induced in the conductor. This principle encompasses all conductors that cut magnetic lines of flux, including the armature conductors of a DC motor.

Figure 4 shows how the right-hand rule establishes clockwise rotation for the motor. If the left-hand rule to the generator is applied, it can be seen that clockwise rotation will induce an emf in the opposite direction. A motor and a generator are essentially the same machine, and it is apparent that:

> *The motion of the armature conductors cutting the field in a DC motor results in an induced emf that opposes the applied emf that is producing the armature current.*

The fact that the induced emf opposes the applied emf gives rise to the terms *counter emf* and *back emf*. The existence of the counter emf suggests that not all of the applied emf will produce current as determined by Ohm's law. For example, consider a 10-hp, 240-volt DC motor with an armature resistance of 2 ohms. Ohm's law would indicate an armature current of 120 amps. In fact, the full-load current rating for this motor is 38 amps.

It can be determined that the value of the counter emf from the generated voltage (E_g) formula introduced in Chapter 2 of this book:

$$E_g = k\Phi N$$

The term *effective voltage* is used for the product of armature current and armature resistance (IR) and represents the difference between the applied voltage and the counter emf. This relationship can be summarized with the following formula:

$$I_A R_A = E_a - E_g$$

where:

I_A = armature current

R_A = armature resistance

Ea = applied voltage

Eg = counter emf

Motor starting current

The foregoing formula for effective voltage can be used to examine the starting conditions of a DC motor. By cross-multiplication, armature current (I_A) is:

$$I_A = \frac{E_a - E_g}{R_A}$$

At standstill, the motor speed (N) is zero. Therefore, counter emf ($E_g = k\Phi N$) equals zero. In the absence of counter emf, the full value of applied voltage results in extremely high current because it is limited only by the resistance of the armature. In practice, DC motors up to 2 hp have sufficient resistance to withstand starting current, and can be started across the line.

If full-line voltage is applied to a large DC motor, the starting current may damage the motor, trip the overcurrent device or subject the load to excessive mechanical stress. When starting large motors, resistance is placed in series with the armature to limit the current to a safe value. Typically the value of this current is 1.5 times the full-load current. As the motor accelerates, the counter emf builds up and the starting resistance is gradually reduced.

The starting resistors and associated control equipment are called *reduced voltage starters*. The starting resistance is usually reduced in fixed increments, which may be achieved by manual or automatic circuits.

Locked rotor conditions

Although electrical problems such as incorrect connections or an open circuit could prevent a motor from starting, a locked rotor in a DC motor usually indicates mechanical problems. The motor fails to start because it is unable to provide sufficient torque to accelerate the load.

Mechanical causes include excessive load or badly worn or seized bearings. Improper starting voltage for the load conditions would also prevent the motor from developing sufficient torque.

The locked rotor condition causes the high starting current to continue. This may damage the motor through overheating.

Mechanical loading

Knowing the significance of counter emf is essential for a person to understand the process of mechanical loading of a DC motor. Consider a DC motor operating at rated speed under less than full-load conditions. When mechanical load is increased on the shaft of the motor, the following conditions occur:

- An increase in mechanical load causes the motor speed to decrease.
- The decrease in speed causes a reduction in counter emf ($\mathrm{E_g = k\Phi N}$).
- The decrease in counter emf causes an increase in effective voltage ($\mathrm{I_A R_A = E_a - E_g}$).
- The increase in effective voltage causes an increase in armature current.
- The increase in armature current causes an increase in torque, to balance the increased mechanical load on the shaft ($\mathrm{T = k\Phi I}$).

If the increase in mechanical load exceeds the motor's ability to develop additional torque, the motor will stall and draw excessive current. The overcurrent protection should disconnect the motor from the line.

The reverse effect occurs when mechanical load is decreased. As load is decreased, the motor speeds up. The increase in speed causes the counter emf to increase, thereby decreasing effective voltage and armature current. The resulting torque again matches the new conditions of mechanical load.

Torque and horsepower

The torque (T) developed by a motor can be considered as an equivalent force (F) acting through the radial distance (R) of the armature. The work done in one revolution would be the equivalent force acting through the circumference (2πR) of the armature.

$$\text{Work} = \text{F} \times 2\pi\text{R}$$

$$= 2\pi T$$

Since power is the rate of doing work, the rotational speed of the motor can be used to determine power.

Power = work per second

In one second, the armature turns N/60 revolutions, where N is the rpm of the motor. Therefore:

$$\frac{\text{Work}}{\text{sec}} = 2\pi\text{T}\left(\frac{\text{N}}{60}\right)$$

$$\text{Power} = \frac{2\pi\text{TN}}{60}$$

In the SI system, power is in watts, torque is in newton-metres, and speed is in rpm. It is still common in North America to rate motors in horsepower, and most texts express the relationship between torque, speed and power in imperial units. As one horsepower is equivalent to 550 foot-pounds per second, the power formula is as follows:

$$\text{hp} = \frac{2\pi\text{TN}}{60 \times 550}$$

$$= \frac{2 \times 3.14 \times \text{TN}}{33000}$$

$$= \frac{\text{TN}}{5252}$$

where:

T = torque in pounds-feet

N = rotational speed in revolutions per minute

1 hp, the imperial measurement for power, is equal to approximately 746 watts, the SI measurement for power.

As a rule of thumb, torque in lb/ft × 746/550, equals torque in newton-metres.

Speed regulation

When selecting a DC motor for a specific application, it is important to consider how the motor speed is affected by changes in mechanical load. This variation in speed with load is called *speed regulation*. The change in speed is expressed as a percentage of the rated or full-load speed:

$$\%\ \text{regulation} = \frac{\mathrm{N_{NL}} - \mathrm{N_{FL}}}{\mathrm{N_{FL}}} \times 100\%$$

where:

N_{NL} = no-load speed in rpm

N_{FL} = full-load speed in rpm

DC motors are well suited to applications that require smooth speed control under a wide range of load conditions. The specific characteristics of series, shunt and compound motors will be discussed later in this Learning Guide.

Base speed

DC motors have a normal or base speed at which they will operate without any speed control device in operation. The base speed will vary with mechanical load conditions.

Power is proportional to the product of torque and speed. Operating a DC motor at other than its base speed will affect its ability to deliver rated horsepower at torque levels required to drive the mechanical load.

Above base speed

The current drawn by a DC motor is a function of the counter emf developed by the armature. If a rheostat is placed in the shunt field circuit, the field current will decrease. The decrease in flux will cause the counter emf to decrease and the armature current to increase.

Contrary to what one would expect, the increase in armature current is greater than the decrease in excitation. As a result, the torque ($T = k\Phi I$) increases and the motor speeds up. Inserting resistance in the shunt field circuit causes a DC motor to operate above base speed.

Below base speed

To operate a motor below its base speed, it is necessary to reduce armature current by adding resistance in series with the armature. The high levels of armature current would require physically large (and expensive) rheostats that result in very high heat loss.

A more practical solution to operating below base speed involves electronic devices that are capable of controlling the voltage applied to the armature.

Armature reaction

In both DC generators and DC motors, armature current produces a magnetic field that distorts the main field of the machine. The field distortion caused by armature current is called *armature reaction*. Adverse effects include a weakening of the main field and excessive sparking at the brushes.

For the same main field polarity and direction of rotation, the direction of armature current in a motor is opposite to that in a generator. The magnetic polarity of the armature flux will also be opposite, producing the field distortion shown in Figure 5. The motor armature current causes the electrical neutral plane to shift in the direction opposite to the direction of rotation. Sparking can be reduced by shifting the brushes opposite to the direction of rotation.

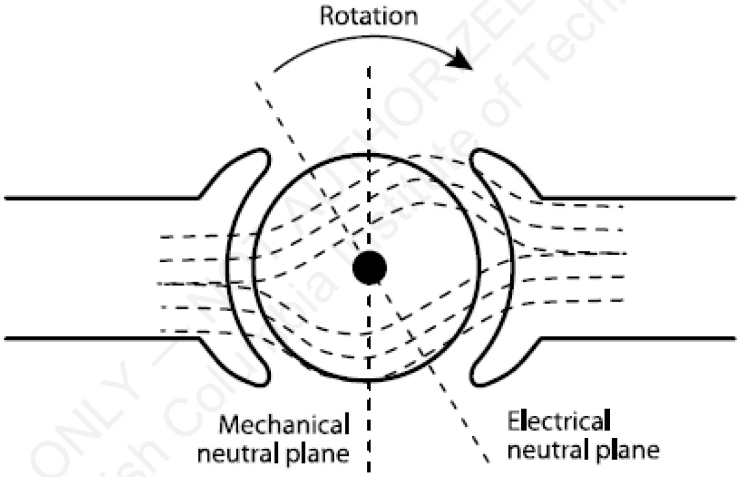


Figure 5 Main field distortion

Interpoles

In practice, the mechanical load conditions on a DC motor would necessitate continual shifts in brush position to reduce sparking. Interpoles placed between the main field poles (Figure 6) provide a more satisfactory way of minimizing the distorting effect of armature flux.

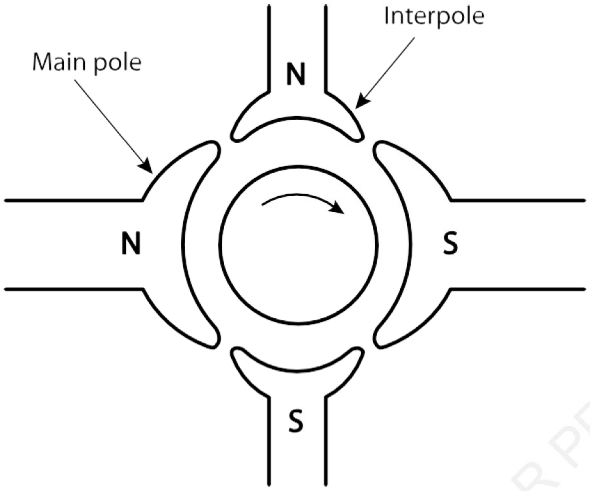


Figure 6 Interpoles

To correct for the shift in the neutral plane, a motor interpole must have the same magnetic polarity as the main pole directly behind it with respect to the direction of rotation. Interpoles are connected in series with the armature so that the strength of the interpole matches the strength of the armature field.

Interpoles have narrow field cores and consist of a few turns of heavy-gauge wire. To minimize the possibility of an incorrect connection, the interpole windings are usually included with the armature between leads A_1 and A_2. They are found in most shunt and compound DC machines above ½ hp.

Compensating windings

Compensating windings, embedded in the face of the main field poles, provide the most effective method of countering the effects of armature reaction. Due to their high cost, however, compensating windings are seldom used in DC motors.

Applications that require compensating windings involve large DC motors subjected to sudden variations in load conditions. In this instance, compensating windings are used in conjunction with interpoles. Both compensating windings and interpoles are series-connected to the armature.

Calculations involving DC motors

The main tools for making calculations involving voltage and current are Ohm's law and Kirchhoff's law. An understanding of effective voltage and the role of counter emf is essential.

Example 1: A 240-volt motor operating at full load develops a counter emf of 222 volts. If the resistance of the armature is 1.5 ohms, determine the armature current.

$$
\begin{aligned}
I_A &= \frac{E_a - E_g}{R_A} \\
&= \frac{(240 - 222)\mathrm{V}}{1.5\ \Omega} \\
&= 12\ \mathrm{A}
\end{aligned}
$$

For compound motors, a more complete problem would include the current drawn by the shunt field and the voltage drop of the series field. It may help to read further in this book before reviewing Example 2.

Example 2: A long-shunt 240-volt compound motor draws 20 amps from the line (Figure 7). Resistance values are:

- Armature resistance RA = 1.2 ohms
- Series field resistance RS = 0.6 ohms
- Shunt field resistance RF = 120 ohms

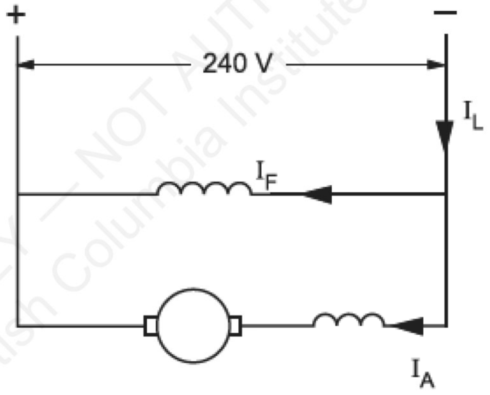


Figure 7 Compound motor

Using the given resistance values, determine (a) armature current, (b) voltage across the armature and (c) counter emf.

Solution:

(a) Armature current

Determine current in the armature path by using Kirchhoff's current law. The line current must be the sum of the currents in the armature circuit and the shunt field.

$$I_L = I_A + I_F$$

where:

I_L = line current

I_A = armature current

I_F = shunt field current

Use Ohm's law to find the shunt field current:

$$
\begin{aligned}
I_F &= \frac{E_a}{R_F} \\
&= \frac{240\ V}{120\ \Omega} \\
&= 2A
\end{aligned}
$$

By transposing the equation derived from the current law, armature current can be isolated.

$$
\begin{aligned}
I_A &= I_L - I_F \\
&= 20A - 2A \\
&= 18A
\end{aligned}
$$

(b) Voltage across armature

The voltage across the armature is the applied voltage minus the IR drop of the series field. Determine it using Kirchhoff's voltage law:

$$E_A = E_a - E_s$$

where:

E_A = voltage across the armature

E_a = applied voltage

E_S = IR drop of the series field

E_S = 18 A (0.6 Ω)

= 10.8 V

$$
\begin{aligned}
E_A &= E_a - E_s \\
&= 240\ V - 10.8\ V \\
&= 229.2\ V
\end{aligned}
$$

This armature voltage becomes the applied voltage when determining the counter emf in part (c) of the calculation.

(c) Counter emf

The counter emf will be determined from the equation:

Effective voltage $\mathrm{I_A R_A = E_A - E_g}$

Remember that the voltage applied to the armature has been reduced by the IR drop of the series field. Transposing this equation:

$$\begin{aligned}\mathrm{E_g} &= \mathrm{E_A - I_A R_A}\\ &= 229.2\ \mathrm{V} - 18\ \mathrm{A}\ (1.2\Omega)\\ &= 207.6\ \mathrm{V}\end{aligned}$$

Example 3: A DC motor operating at 1800 rpm develops a torque of 40 newton-metres. Calculate the power in kilowatts delivered to the mechanical load.

$$\begin{aligned}\mathrm{Power} &= \frac{2\pi \mathrm{TN}}{60}\\ &= \frac{2 \times 3.14 \times 40 \times 1800}{60}\\ &= 7540\ \mathrm{W} \quad \text{or} = 7.54\ \mathrm{kW}\end{aligned}$$

Example 4: Calculate the torque developed on the shaft of a motor that is delivering 15 kW to a mechanical load at 1200 rpm.

By cross multiplying we obtain:

$$\begin{aligned}\mathrm{T} &= \frac{\mathrm{P} \times 60}{2\pi \mathrm{N}}\\ &= \frac{1500 * \times 60}{2 \times 3.14 \times 1200}\ \text{newton} - \text{meters}\\ &= 120\ \mathrm{Nm}\end{aligned}$$

* remember to convert kilowatts to watts

Example 5: Calculate the horsepower delivered by a motor that develops a torque of 75 pounds- feet at 1750 rpm.

$$\begin{aligned}\mathrm{hp} &= \frac{\mathrm{TN}}{5252}\\ &= \frac{75 \times 1750}{5252} = 25\end{aligned}$$

Example 6: Calculate the speed of a motor that is developing a torque of 45 pounds-feet when delivering 10 hp to a mechanical load.

By rearranging the hp formula we obtain:

$$\begin{aligned} \mathrm{N} &= \frac{5252 \times \mathrm{hp}}{\mathrm{T}} \\ &= \frac{5252 \times 10}{45} \\ &= 21167 \text{ rpm} \end{aligned}$$

Example 7: A DC motor has a rated speed of 1800 rpm. Find the speed regulation if the no-load speed is 1850 rpm.

$$\begin{aligned} \%\text{ regulation} &= \frac{\mathrm{N_{NL}} - \mathrm{N_{FL}}}{\mathrm{N_{FL}}} \times 100\% \\ &= \frac{1850 - 1800}{1800} \times 100\% \\ &= 2.78\% \end{aligned}$$

Example 8: Find the no-load speed (NNL) of a DC motor that has a rated full-load speed NFL =1800 rpm with a speed regulation of 2%.

$$\begin{aligned} \%\text{ regulation} &= \frac{\mathrm{N_{NL}} - \mathrm{N_{FL}}}{\mathrm{N_{FL}}} \times 100\% \\ 2\% &= \frac{\mathrm{N_{NL}} - \mathrm{N_{FL}}}{\mathrm{N_{FL}}} \times 100\% \\ \frac{\mathrm{N_{NL}} - \mathrm{N_{FL}}}{\mathrm{N_{FL}}} &= 0.02 \\ \mathrm{N_{NL}} - \mathrm{N_{FL}} &= 0.2\mathrm{N_{FL}} \\ \mathrm{N_{NL}} &= 1.02\mathrm{N_{FL}} \\ &= 1.02 \times 1800 \\ &= 1836 \text{ rpm} \end{aligned}$$

☑ Now do Self-Test 1 and check the answers.

Self-Test 1

1. Define *torque*.

2. Define the *motor effect* principle of magnetism.

3. Fleming's right-hand motor rule is used to determine ______________________ .

4. How does the operation of the armature differ between a DC generator and a DC motor?

5. State two ways in which the direction of rotation of a DC motor can be reversed.

6. Torque is directly proportional to the product of __________________________ and ______________________ .

7. The motion of armature conductors cutting a field results in an induced emf that ____________________ the applied emf.

8. The emf induced in armature conductors as they cut the magnetic field is called ______________________ .

9. The counter emf of a motor is proportional to ____________________________ and ________________________ .

10. Effective armature voltage is the product of ______________ and ______________ .

11. The difference between applied voltage and counter emf is called _____________ .

12. At standstill, the counter emf of a motor is _______________ .

13. At start-up, the current drawn by a DC motor is limited only by ________________ .

14. How is the starting current limited to a safe value in large DC motors?

15. A locked rotor usually means that the motor will _____________________________ .

16. Why is a locked rotor condition undesirable?

17. An increase in mechanical load on the shaft of a motor causes motor speed to ______________________.

18. When the speed of a motor decreases due to an increase in mechanical load, the counter emf __________ .

19. A reduction in counter emf causes armature current to _________________ .

20. What would happen if an increase in mechanical load exceeded the ability of the motor to develop additional torque?

21. In a motor, power is proportional to ____________________ and __________________ .

22. The variation in motor speed with load is called ________________________________ .

23. Determine the percent speed regulation of a 1200-rpm DC motor with a no-load speed of 1260 rpm.

24. The speed at which a DC motor operates without speed control devices is called

______________________ .

25. Why does increasing the resistance in the field circuit of a DC motor cause the speed to increase?

26. To operate a motor below base speed, it is necessary to decrease _______________ .

27. A practical method of operating below base speed involves controlling

28. List two adverse effects of armature reaction if it remains uncorrected.

29. The most common solution for minimizing the effects of armature reaction involves the use of ________________ .

30. Why are interpoles connected in series with the armature?

31. Calculate the armature current of a 120-volt DC motor that is developing a counter emf of 112 volts with an armature resistance of 2 ohms.

32. A 480-volt long-shunt compound motor draws 51 amps from the line when operating under load. The armature resistance is 1.8 ohms, the series field resistance is 1.2 ohms, and the shunt field resistance is 160 ohms. Determine each of the following:
    - Shunt field current
    - Armature current
    - Voltage across the armature
    - Counter emf developed by the armature

33. Calculate the torque developed by a DC motor when delivering 10 hp at 1200 rpm.

34. Calculate the percent speed regulation of a DC motor that has a full-load speed of 1800 rpm and a no-load speed of 1840 rpm.

35. Calculate the no-load speed of a DC motor that has a full-load speed of 2400 rpm and a speed regulation of 3%.

Chapter 2: Describe the features and operating characteristics of the shunt motor

As discussed earlier, shunt field windings consist of a large number of turns of small-gauge wire. In a DC shunt motor, the field excitation is provided by shunt field windings connected in parallel with the armature.

Connection diagrams

NEMA subscripts are used to establish standard field connections with respect to the armature. Earlier the convention of A_1 negative for clockwise rotation of DC generators was discussed. The directions of armature current for a shunt generator and a motor with the same direction of rotation are exactly opposite to one another. Essentially, they are the same machine. Figure 1 shows the direction of armature current and the electrical connections for both machines with the same direction of rotation.

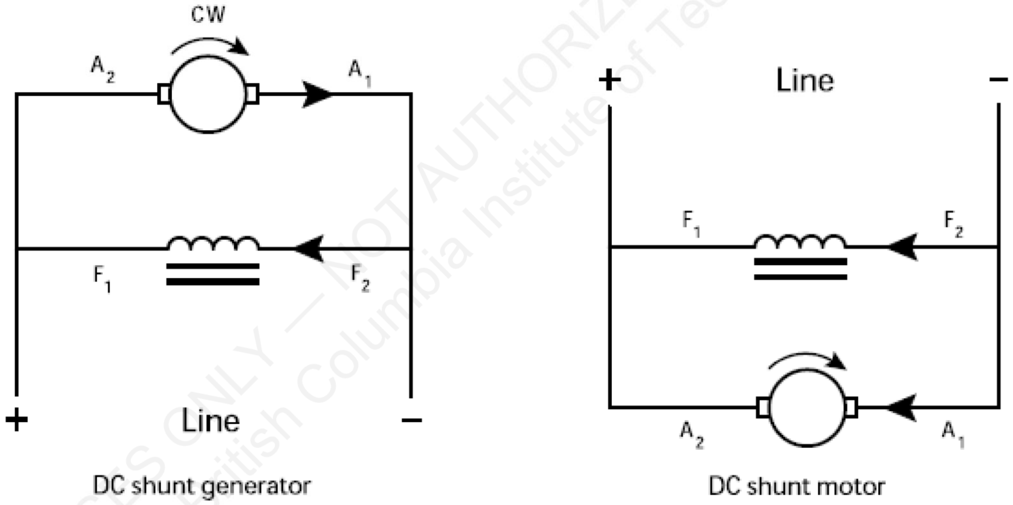


Figure 1 Comparison of generator and motor connections

In the generator, the armature is a source of emf with electron current flowing from A_2 to A_1, making A_1 negative. The armature of the motor, however, is a load. With motor lead A_1 connected to the negative terminal of the supply, electron current will flow from A_1 to A_2 (opposite to the generator armature as shown at the top of Figure 1). In both cases, the shunt fields are connected across the same voltage polarity with current flowing from F_2 to F_1. The magnetic polarity of the fields is the same in both machines. No change in the connections would be required to operate the generator as a motor, and the direction of rotation would remain the same.

Reversing rotation

To reverse the direction of the force acting on the armature conductors, it is necessary to reverse the current direction in either the armature or the field. Unlike in the generator, residual magnetism does not play a role in the operation of a DC motor. Figure 2 shows the connections for changing the direction of rotation to CCW (counter-clockwise). Compare this standard convention to the connection shown in Figure 1.

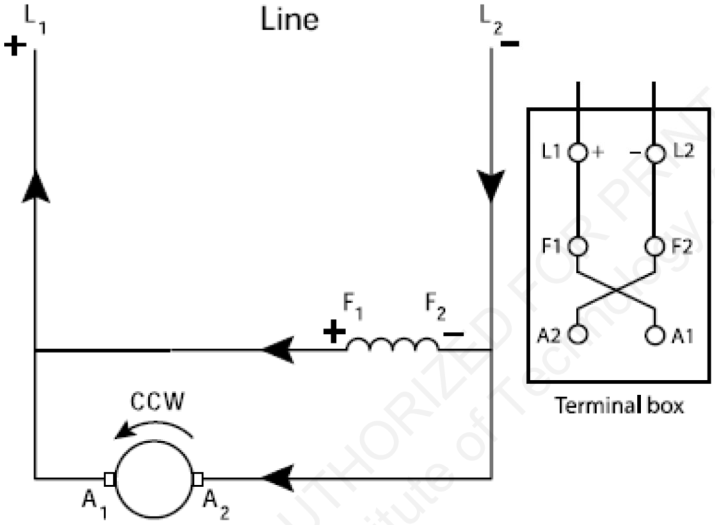


Figure 2 Reversing rotation of a shunt motor

In practice, the direction of motor rotation is changed by reversing the armature leads.

Figure 3 shows the effect of changing only the polarity of the line terminals. In this case, the current changes direction in both the armature and the shunt field, and the direction of rotation remains unchanged.

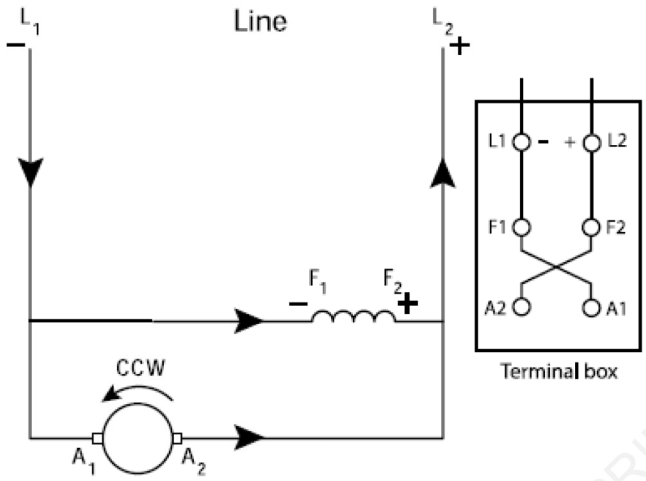


Figure 3 Reversing line connections

Speed regulation and control

The field of a shunt motor is connected across the line (Figure 2). In the absence of a field rheostat, the field current and flux are constant. From the equations $I_A R_A = E_a - E_g$ and $E_g = k\Phi N$, speed in rpm can be expressed as follows:

$$N = \frac{E_a - I_A R_A}{k\phi}$$

where:

E_a, R_A, k and Φ are constant and I is the only variable.

The change in current is such that the full-load speed is roughly 95% of the no-load speed. Shunt motors are commonly called *constant-speed motors*. Figure 4 shows the variation of speed with load.

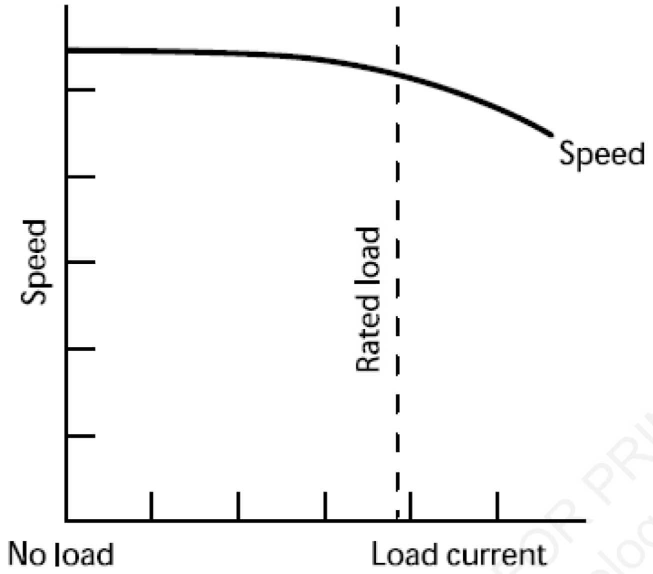


Figure 4 Speed characteristics of the shunt motor

R Review the principles of speed control explained in Chapter 4 of this Learning Guide.

One can enable a DC motor to operate above base speed by inserting a rheostat in the field circuit (Figure 5). If limited speed control is needed, use a shunt motor with a base speed equal to the lowest value of speed required by the application. As the ohmic value of the rheostat is increased, the operating speed of the motor will also increase.

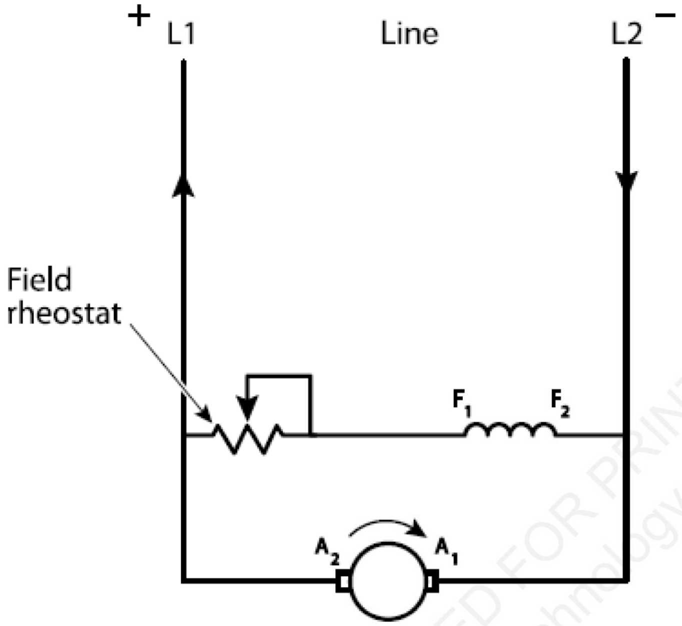


Figure 5 Shunt motor with field rheostat

Because the speed of a shunt motor increases with resistance in the field circuit, extreme care must be taken to ensure that the field circuit does not become open during operation. For this reason, the field is never fused. With drastically reduced counter emf, the motor draws very high current. Residual magnetism provides sufficient excitation for the motor to accelerate to unsafe speeds. This condition is called *runaway*. Over-speed sensors or loss-of-field relays are commonly used to detect over-speed conditions and initiate a safe shutdown of the motor.

⚡ Never allow the field circuit to open during operation of a DC shunt motor.

Most applications for DC shunt motors require operation below base speed. The very high-power losses associated with the insertion of resistance in the armature circuit have led to the development of electronic circuits that vary the voltage applied to the armature in order to control the speed below base speed.

Torque characteristics

If the excitation of a shunt motor is held constant, the torque varies directly with armature current (Figure 6). The starting torque of a shunt motor is typically 2.5 to 3 times the full-load torque and is not sufficient for starting heavy loads.

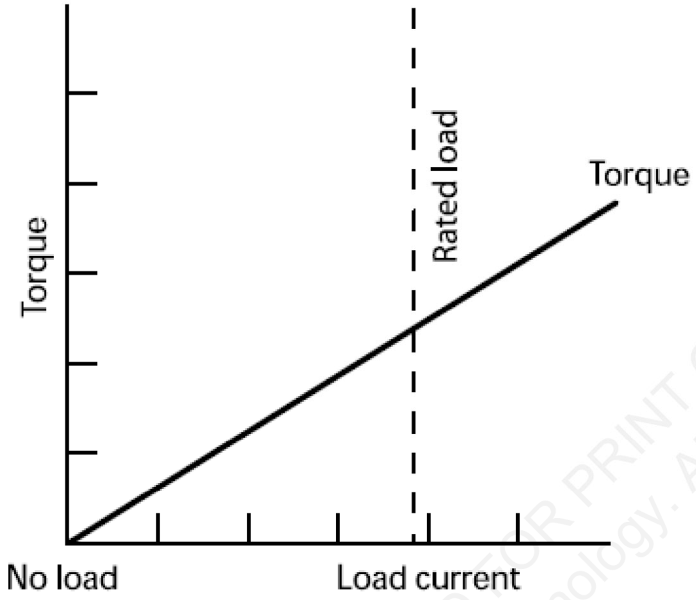


Figure 6 Torque characteristics of a shunt motor

Applications

DC shunt motors are most commonly used in constant-speed applications where a large variation in speed with load is undesirable. Typical uses include drives for paper machines, printing presses, drill presses, lathes, blower, and motor-generator sets.

Shunt motors are not suitable for starting under heavy-load applications such as traction (locomotives) and lifting (cranes) equipment.

☑ Now do Self-Test 2 and check the answers.

Self-Test 2

1. Shunt field windings consist of a:
   a. large number of turns of large-gauge wire
   b. small number of turns of large-gauge wire
   c. large number of turns of small-gauge wire
   d. small number of turns of small-gauge wire

2. Excitation of a shunt motor is provided by field coils connected in series with the armature.
   a. True
   b. False

3. When using NEMA subscripts, the convention of A_1 positive indicates (CCW or CW) rotation.

4. When a DC generator and a DC motor are operated with the same line voltage, polarity and direction of rotation, the respective armature currents will be in opposite directions.
   a. True
   b. False

5. State two ways to reverse the direction of the force acting on the armature conductors of a shunt motor.

6. What is the most practical method of reversing the direction of rotation of a shunt motor?
   a. Reverse the armature leads.
   b. Reverse the shunt field leads.
   c. Reverse both the armature and shunt field leads.
   d. Reverse the line connections.

7. What happens to the direction of rotation if the polarity of the line terminals is reversed?

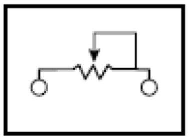
8. A shunt motor is commonly called a ______________________________ motor.

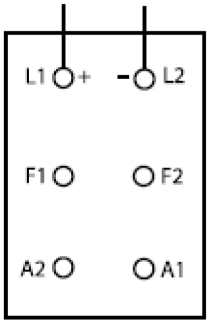
9. Why must the field circuit of a shunt motor never be allowed to become open while the motor is in operation?

10. To prevent runaway in a shunt motor, an __________________________ is used.

11. List three typical uses for a shunt motor.

12. Draw the connection diagram for a DC shunt motor with field rheostat. The motor is to rotate in a clockwise direction. Label all components according to NEMA standards and indicate line polarity. Connect the terminal box according to your diagram.





Terminal box

Chapter 3: Describe the features and operating characteristics of the series motor

Series field windings consist of a few turns of large-gauge wire and carry the full armature current. Unlike shunt field coils, the magnetic strength of the series field coils varies with load current.

Connection diagrams

Figure 1 shows the electrical connection of a series motor for counter-clockwise rotation.

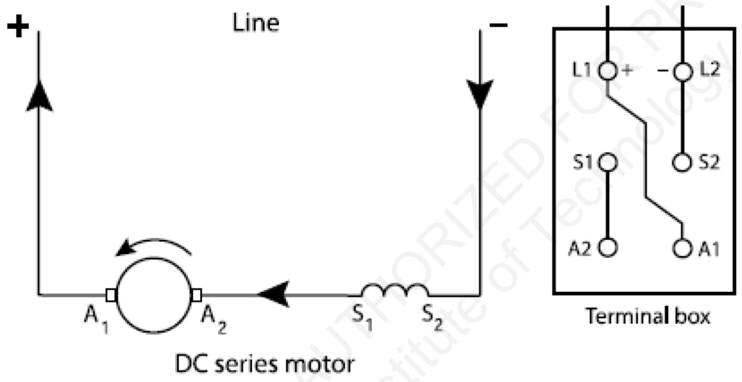


Figure 1 Connection diagram

Reversing rotation

The direction of rotation is determined by the direction of the force acting on the armature conductors. Rotation can be reversed by interchanging the leads of either the armature (A_1–A_2) or the series field (S_1–S_2), as shown in Figure 2. Compare the two diagrams in Figure 2 to the motor diagram in Figure 1.

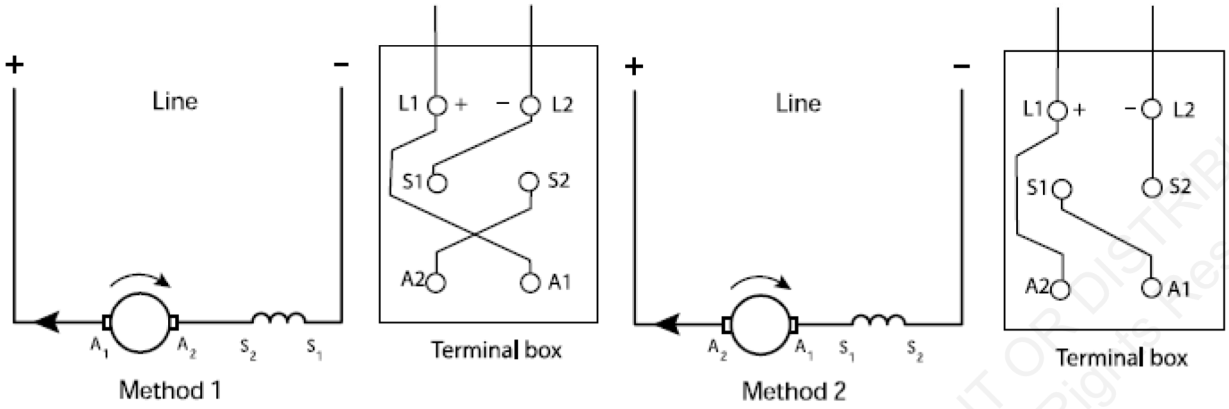

+
Line
-
L1
+
-
L2
S1
S2
A2
A1
Terminal box
A_1
A_2
S_2
S_1
Method 1
+
Line
-
L1
+
-
L2
S1
S2
A2
A1
Terminal box
A_2
A_1
S_1
S_2
Method 2

Figure 2 Reversing rotation of a series motor

Changing the polarity of the line leads reverses the current direction in the armature and also changes the magnetic polarity of the series field poles. In this instance, the direction of rotation is as shown in Figure 3. Compare this to the motor connection in Figure 1.

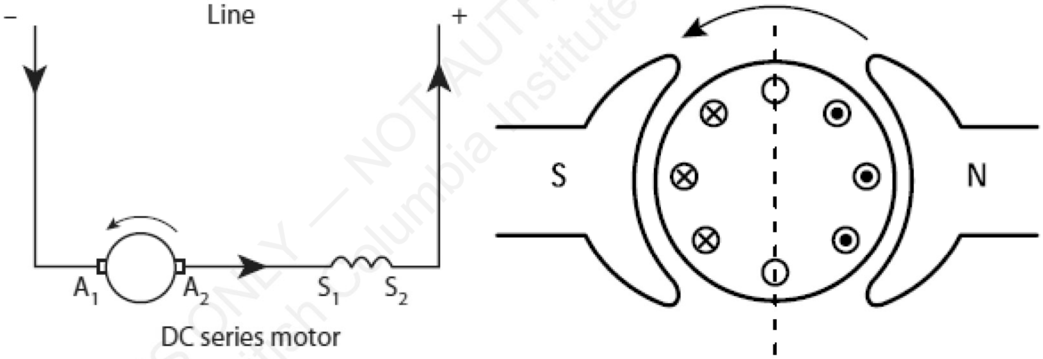

-
Line
+
A_1
A_2
S_1
S_2
DC series motor
S
N

Figure 3 Reversing line connections

Speed regulation and control

In the shunt motor, the strength of the field poles is relatively independent of armature current. This results in very small variations in speed with load. In the series motor, the strength of the magnetic field increases with armature current. Every change in load (armature current) produces a change in both current and excitation.

Torque is proportional to the product of flux and current ($T = k\Phi I$). Assuming a linear relationship between current and excitation, torque varies with the square of the armature current (Figure 4). As mentioned in Chapter 4, it is the counter emf developed by the motor ($E_g = k\Phi N$) that limits the current to a value consistent with the required torque. The increase in excitation (armature current) is accompanied by a corresponding decrease in speed (Figure 5).

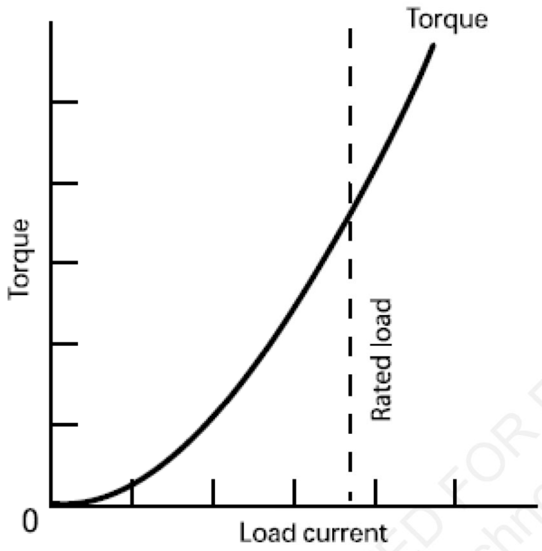


Figure 4 Torque characteristics of a series motor

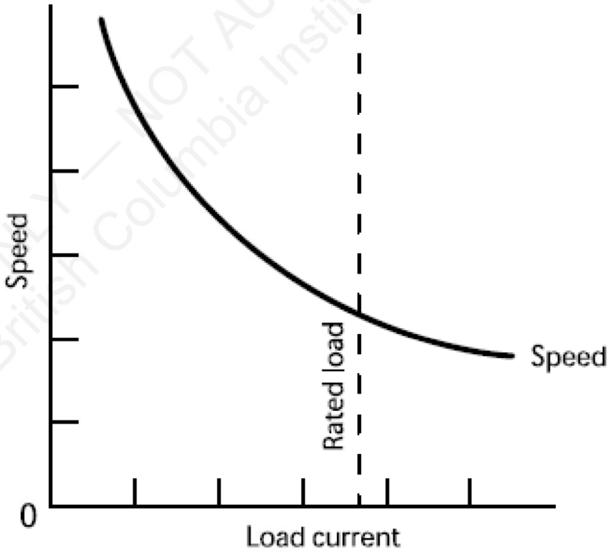


Figure 5 Speed characteristics of a series motor

The wide variation in speed with load makes the series motor unsuitable for constant-speed applications.

Speed control of a series motor can only be achieved by limiting armature current. The high-power losses associated with resistance in series with the armature make this method of speed control impractical for large motors. In practice, solid-state drives are used to reduce the voltage applied to the motor.

Torque characteristics

When starting a series motor, the absence of counter emf results in very high current. This high current produces very high excitation as it passes through the series field. The combination of high current and flux produces extremely high starting torque—as much as five times the full-load value.

A major concern when operating series motors is the effect of the sudden removal of load when the machine is operating. Since torque is proportional to the square of the current, the series motor rapidly accelerates to unsafe operating speeds if the load is suddenly removed. For this reason, belt drives that can slip or break should not be used with series motors.

Always mechanically couple a series motor directly to its load.

Applications

The main characteristics of the series motor are its very high starting torque and very poor speed regulation. In traction and lifting applications, speed variation is not objectionable and high starting torque is used to advantage. Common uses include cranes, hoists, locomotives, mine haulage trucks and automobile starters.

☑ Now do Self-Test 3 and check the answers.

Self-Test 3

1. Series field windings consist of a:
    a. large number of turns of large-gauge wire
    b. small number of turns of large-gauge wire
    c. large number of turns of small-gauge wire
    d. small number of turns of small-gauge wire

2. What is the main difference between series and shunt excitation?

3. State two ways to reverse the direction of rotation of a series motor.

4. Will changing the polarity of the line leads change the direction of rotation of a series motor? Why?

5. Why is the series motor unsuitable for constant-speed applications?

6. In practice, speed control of series motors is accomplished using ________________ .

7. The main advantage of the series motor is its very high starting torque.
   a. True
   b. False

8. Why should a series motor always be mechanically coupled to the driven load?

9. The main characteristics of the series motor are ________________________________ and ______________________.

10. List three common uses for series motors.

Chapter 4: Describe the features and operating characteristics of the compound motor

Many applications require a motor that has higher starting and running torque, while still retaining the speed regulation and control available from the shunt motor. These characteristics are available in the compound motor, which has both shunt and series field coils. In most compound motors, the characteristics are predominantly shunt, with a few turns of series field to improve torque.

Connection diagrams

When connecting compound motors, the direction of current in the field windings is critical for proper operation. NEMA subscripts are used to determine whether the series field will aid or oppose the shunt field (by convention, A_1 is shown positive with counterclockwise rotation). As discussed previously, one must consider cumulative versus differential compounding, and long versus short shunt connection.

For DC generators, the general rule is to connect the shunt field across the source of emf. For motors, the long shunt connection is preferred since it eliminates the effect of the series field IR drop from the shunt field winding voltage.

Most applications require cumulative compounding, where the flux of the series field adds to the flux of the shunt field. Figure 1 shows both long and short shunt connections for a cumulative compound motor. For consistency, all connections are shown with electron current flowing from F2 to F1 and from S2 to S1. This way, the shunt and series windings establish the same magnetic polarity on the field poles that they share.

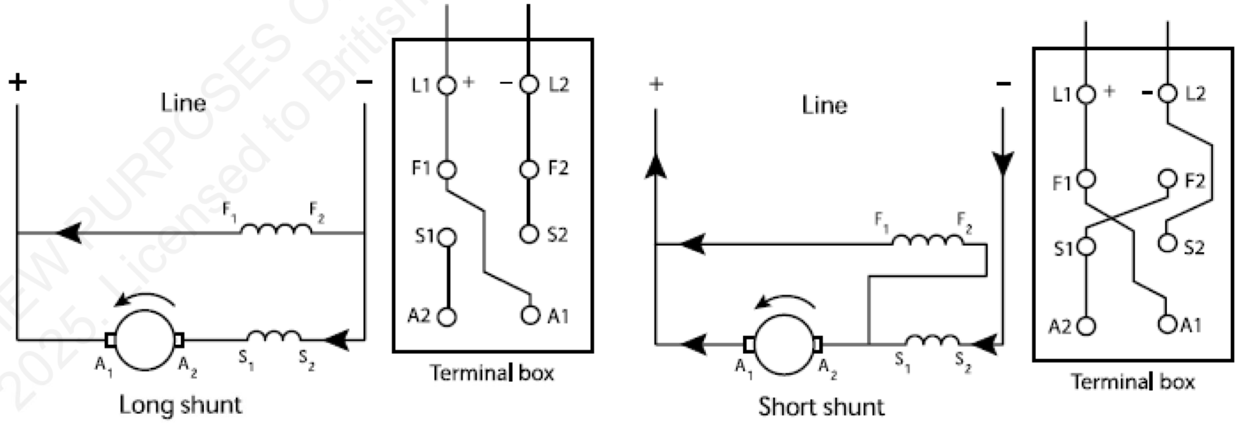
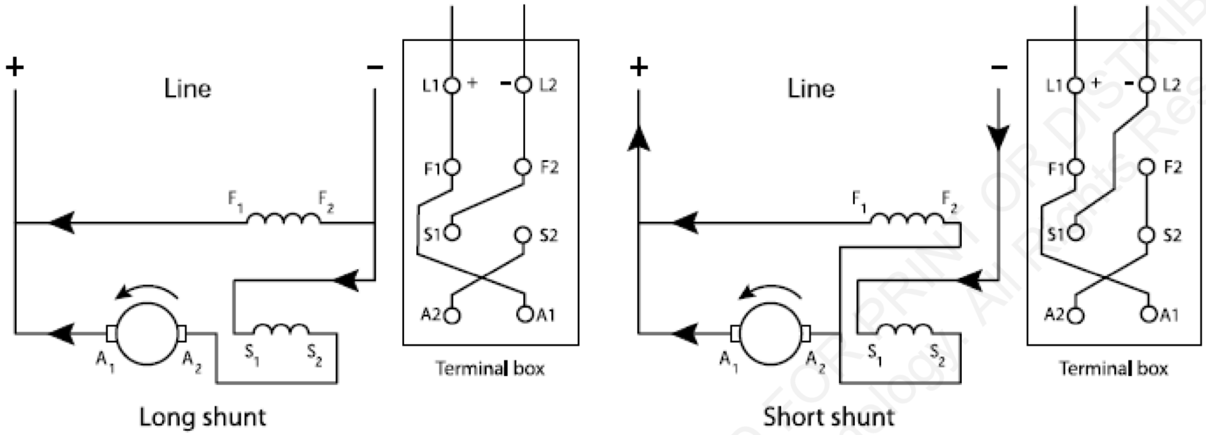


Figure 1 Cumulative compound motor

In extremely rare instances, the series field is connected to produce a flux that will oppose the flux established by the shunt field. This connection is called *differential compound*. Figure 2 shows the connection of a differential compound motor. Note that the current directions in the field coils are from F_2 to F_1 and from S_1 to S_2.



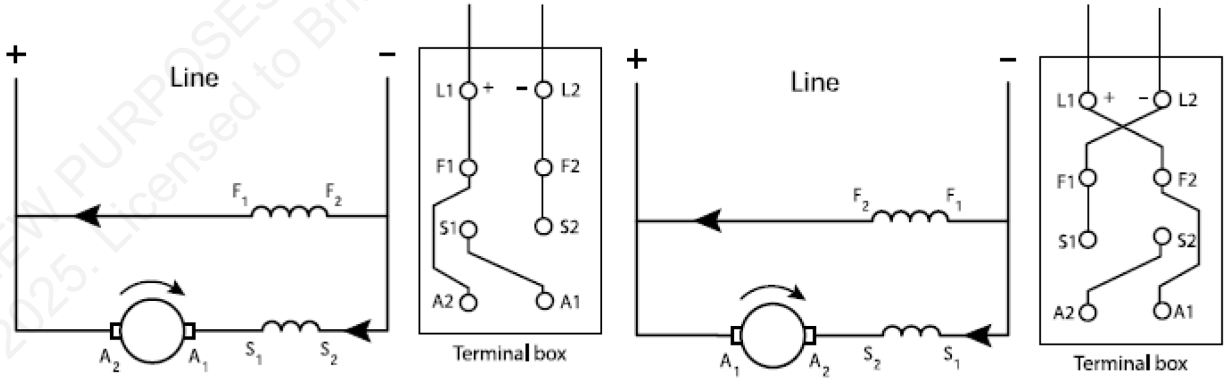
+
Line
−
F_1
F_2
A_1
A_2
S_1
S_2
Long shunt
L1 +
- L2
F1
F2
S1
S2
A2
A1
Terminal box
+
Line
−
F_1
F_2
A_1
A_2
S_1
S_2
Short shunt
L1 +
- L2
F1
F2
S1
S2
A2
A1
Terminal box

Figure 2 Differential compound motor

Reversing rotation

Reversing the direction of rotation of a compound motor can be accomplished by reversing the connection of the armature leads, or both the series and shunt coil leads (Figure 3).

When reversing field connections, take care to ensure that both series and shunt fields are correct with respect to each other. An incorrect connection will change the motor from cumulative to differential, seriously impairing the machine's operating characteristics. In practice, it is simpler to reverse the rotation by reversing the armature leads only.



+
Line
−
F_1
F_2
A_2
A_1
S_1
S_2
L1 +
- L2
F1
F2
S1
S2
A2
A1
Terminal box
+
Line
−
F_2
F_1
A_1
A_2
S_2
S_1
L1 +
- L2
F1
F2
S1
S2
A2
A1
Terminal box

Figure 3 Clockwise rotation

Speed regulation and control

Figure 4 compares the speed curves of the series and shunt motors on the same graph. The speed characteristic of the cumulative compound motor lies between the series and shunt curves. The actual position of the intermediate curve will depend on the degree to which the motor is compounded.

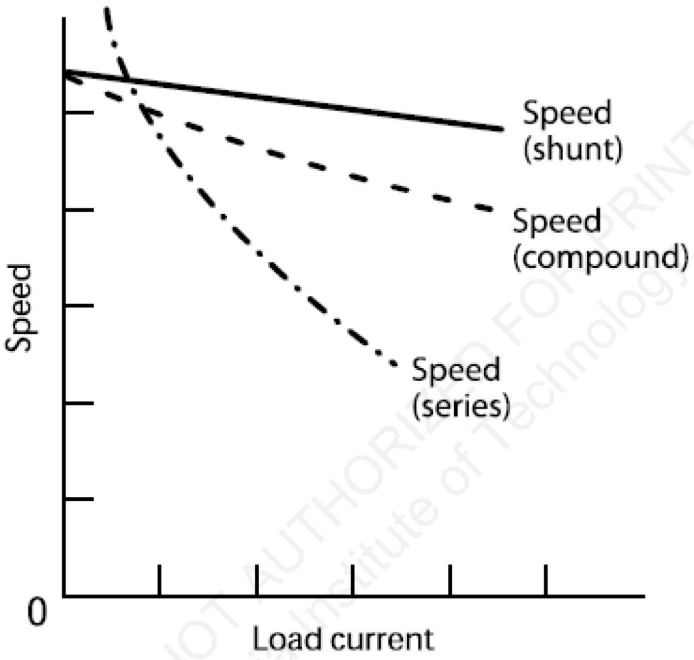


Figure 4 Speed characteristics

As discussed earlier, the speed of a shunt motor can be changed by inserting a rheostat in the shunt field circuit. This method of speed control can also be applied to the compound motor (Figure 5). Electronic adjustable speed drives give the greatest range of speed control.

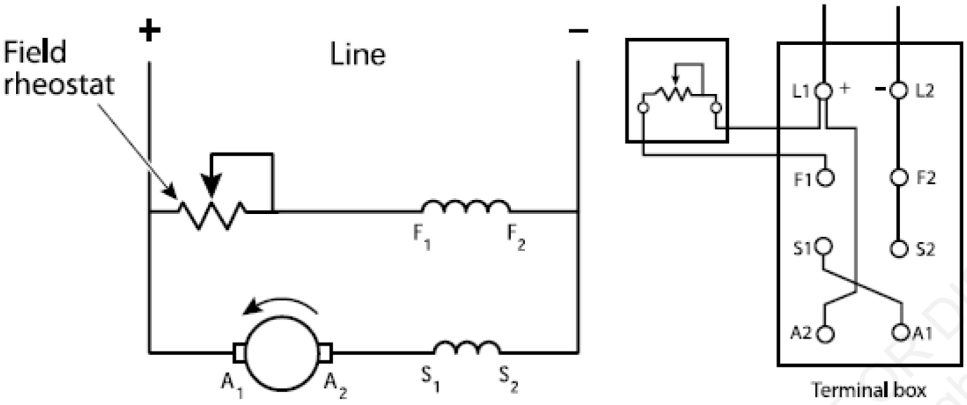


Figure 5 Compound motor with field rheostat

The flux developed by the series field helps to limit the excessive speed increase resulting from an open circuit in the shunt field. In most applications, the flux developed by the series field is considerably less than the flux developed by the shunt field, and dangerous over-speed may still occur. For this reason, to prevent runaway of compound and shunt motors, take the same precautions (such as over-speed centrifugal devices or loss-of-field relays).

Unlike in series motors, the presence of the shunt field provides the compound motor with a fixed no-load speed. For this reason, it is acceptable to belt-drive the mechanical load.

Torque characteristics

Figure 6 compares the torque curves of the series, shunt and compound motors on the same graph. As expected, the torque curve for the compound motor lies between the curves for the series and shunt motors. The degree of compounding determines the actual position of this curve.

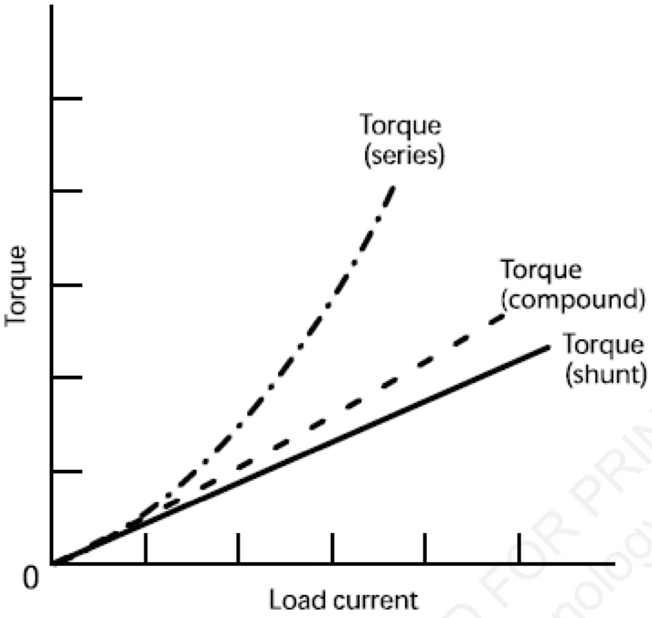


Figure 6 Torque characteristics

In the design of compound motors, the degree of compounding can produce torque characteristics ranging from series to shunt. Be careful to use a motor with torque and speed characteristics that match the specific requirements of the application.

Applications

Compound motors are commonly used in applications that require relatively constant speed under varying load conditions. Compound motors are more suitable than shunt motors for handling sudden increases in mechanical load. Applications include presses, shears, compressors and elevators.

☑ Now do Self-Test 4 and check the answers.

Self-Test 4

1. A compound motor has both ______________________ and _________________ field coils.
2. In most compound motors, the motor characteristics are predominantly like the _______________________motor.
3. When the flux of the series field aids the flux of the shunt field, the connection is called a ______________________ compound.
4. When the flux of the series field opposes the flux of the shunt field, the connection is called a ________________ compound.
5. Explain the difference between long shunt and short shunt connections.
6. State two ways of reversing the direction of rotation of a compound motor.
7. Which of the two methods of reversing rotation in Question 6 is preferred?
8. Figure 4 in Chapter 4 shows the speed characteristics of series, shunt and compound motors. What determines the position of the compound characteristic curve with respect to the series and shunt curves?

9. The speed of a compound motor can be increased by increasing resistance in the shunt field circuit.
    a. True
    b. False

10. Is it necessary to take precautions to prevent runaway of a compound motor?

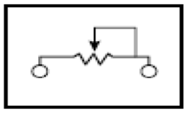
11. Is it acceptable to have belt-driven mechanical loads with a compound motor?

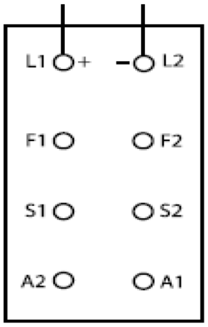
12. When selecting a compound motor, the ________________ and ________________ characteristics must be matched to the specific application.

13. Compound motors are more suitable than shunt motors for handling ___________ .

14. List three applications for compound motors.

15. Draw the connection diagram for a compound DC motor, with a field rheostat for speed control. The motor is to rotate in a counter-clockwise direction. Label all components according to NEMA standards. Show direction of current flow and indicate line polarity. Connect the terminal box according to your diagram





Terminal box

Answer Key

Self-Test 1

1. Torque is a twisting or turning force that is capable of producing rotation about an axis.
2. Whenever a conductor carries current in the presence of a magnetic field, a force will act on the conductor at right angles to the field.
3. the direction of force acting on a conductor
4. In a generator, the armature is a source of emf. In a motor, the armature is a load.
5. - Reverse the connection of the armature leads.
   - Reverse the connection of both the series and shunt field leads.
6. flux, armature current
7. opposes
8. counter emf (or back emf)
9. flux, speed
10. armature current, armature resistance
11. effective voltage
12. zero
13. armature resistance
14. Resistance is placed in series with the armature.
15. fail to start when voltage is applied
16. The persistence of high starting current may damage the motor.
17. decrease
18. decreases
19. increase
20. The motor would stall.
21. torque, speed
22. speed regulation
23. 5%
24. base speed
25. The increase in armature current (due to a decrease in counter emf) is greater than the decrease in excitation.
26. armature current
27. the voltage applied to the armature
28. - Weakening of the main field
    - Excessive brush sparking
29. interpoles
30. So that the strength of the interpole matches the strength of the armature field
31. 4 amps

Self-Test 1

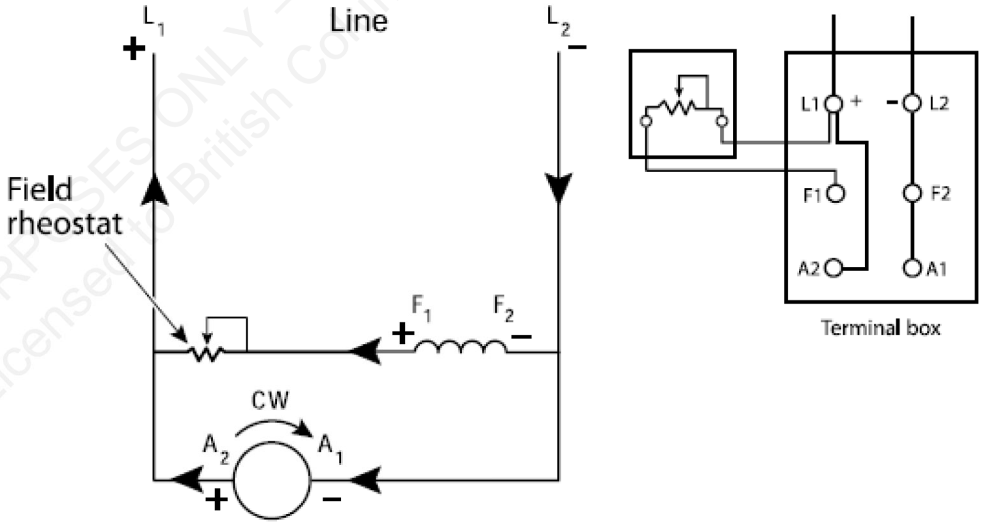
32.
- Shunt field current = 3 amps
- Armature current = 48 amps
- Voltage across armature = 422.4 volts

Counter emf = 336 volts

33. 43.8 pounds-feet
34. 2.2%
35. 2472 rpm

Self-Test 2

1. c. large number of turns of small-gauge wire
2. b. False
3. counter-clockwise (viewed from opposite drive end)
4. a. True
5.
   - Reverse the direction of current in the armature.
   - Reverse the direction of current in the shunt field windings.
6. a. Reverse the armature leads.
7. The rotation remains the same.
8. constant speed
9. The motor can accelerate to unsafe speeds.
10. over-speed sensor (or loss of field relay)
11. drives for paper machines, printing presses, drill presses, lathes, blowers, motor-generator sets
12.

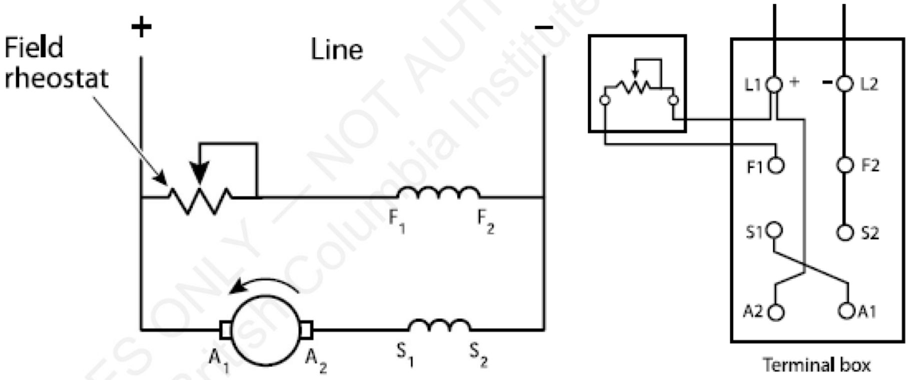


Self-Test 3

1. b. small number of turns of large-gauge wire
2. The magnetic strength of series field coils varies with load current.
3. - Reverse the connection of the armature leads.
   - Reverse the connection of the series field leads.
4. No. Reversing line polarity reverses both armature current and field polarity, maintaining torque in the same direction as before.
5. Since the torque varies with the square of the armature current, changes in mechanical load are accompanied by large changes in operating speed.
6. solid-state drives
7. a. True
8. The sudden removal of load may cause the motor to accelerate to an unsafe speed.
9. high starting torque, poor speed regulation
10. cranes, hoists, locomotives, mine haulage trucks, automobile starters

Self-Test 4

1. shunt, series
2. shunt
3. cumulative
4. differential
5. In the long shunt connection, the shunt field is connected across the line (armature and series field). In the short shunt connection, the shunt field is connected directly across the armature.
6.
   - Reverse the connection of the armature leads
   - Reverse the connection of both the series and shunt field leads.
7. reversing the connection of the armature leads
8. the degree of compounding
9. a. True
10. Yes. The degree of compounding may not be sufficient to prevent dangerous over-speed in the event of an open in the shunt field circuit.
11. Yes. The no-load speed hazard of the series motor is not present.
12. torque, speed
13. sudden increases in mechanical load
14. presses, shears, compressors, elevators
15.



ELECTRICAL TRADES APPRENTICESHIP PROGRAM

MAINTAIN DC MOTORS

Level 3

MAINTAIN DC MOTORS

Chapter 1: Describe the maintenance and troubleshooting for DC motors 2

Answer Key 11

Chapter 1: Describe the maintenance and troubleshooting for DC motors

Operational difficulties with DC motors are due to either electrical faults or mechanical faults. With this in mind, this Learning Task introduces some basic procedures for troubleshooting and maintaining DC motors.

Electrical faults

In general, electrical faults in DC motors result from an open circuit, a short circuit, a ground fault, incorrect connection or improper voltage. For proper operation, keep a motor clean and dry. Conduct insulation tests regularly.

If a DC motor does not perform as it should:

1. Check that the supply voltage is correct and ensure that the armature and field coils are properly connected.
2. Locate open circuits using continuity tests of the field and armature circuits.
3. Use a megger to determine whether there are grounds and insulation breakdown.

Testing the armature for electrical faults

Most electrical faults in DC machines occur in their armature windings. To test the armature for electrical faults, it must first be removed from the machine. Once removed, perform the following tests to identify which type of electrical fault has occurred in the armature.

Testing for an armature faulting to ground

Connect a 120 V supply and a test lamp between any commutator bar and the shaft. If the test lamp lights, the armature windings are in contact with the ground. This fault is commonly known as a grounded coil.

Testing for an open armature circuit

For lap wound armatures, apply a low voltage to two bars on opposite sides of the commutator. Measure the voltage between adjacent bars while moving the leads of the voltmeter around the commutator. Equal voltages should be observed. If there is an open coil or bar, the full applied voltage between the bars connected to the faulty coil will be observed. Excessive sparking at the commutator under normal load and failure to come up to nameplate speed are often indicators of an open armature coil. Often the commutator bars to which the open coil is attached will have burn marks.

Testing for a shorted armature circuit

A growler (see Figure 1) is required for this test. A growler is a device that produces a strong alternating magnetic field. A strong alternating magnetic field will induce a relatively strong alternating voltage into any conductor through which it passes. If that conductor forms a closed loop with relatively low resistance, which a short circuit exemplifies, the induced alternating voltage will result in an intense alternating current passing through the conductor. This alternating current produces a strong alternating magnetic field that surrounds the conductor. A piece of steel placed near the conductor will experience an attraction to it that varies in strength relative to the frequency and intensity of the magnetic field surrounding the conductor.

To perform the test, first place the armature on the energized growler. Next, place a steel strip, such as a hacksaw blade, on top of the armature and along its axis. Now slowly rotate the armature. The steel strip will vibrate excessively when a slot containing a shorted armature winding is directly beneath it. This fault is commonly known as a shorted coil.

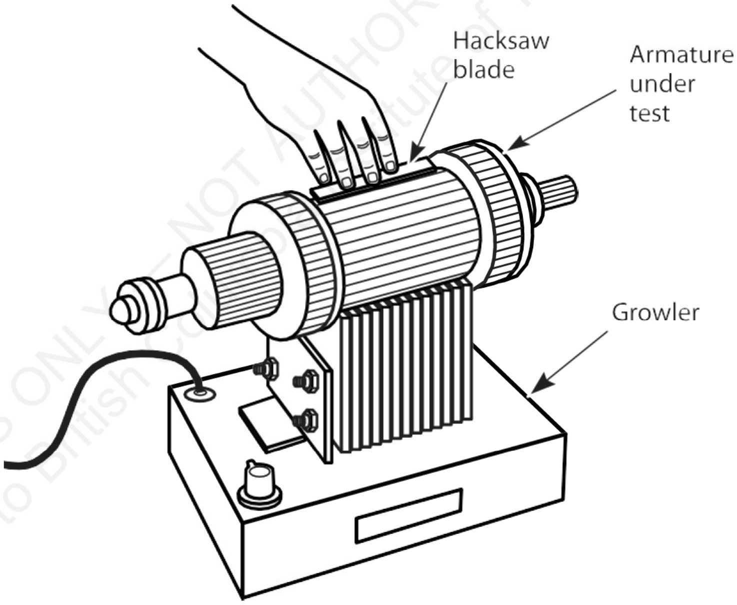


Figure 1 Using a growler to test for shorted coils

Brush/commutator maintenance

When operated correctly, a DC motor should not overheat or spark excessively at the brushes.

Brushes

Brushes must be constantly checked during operation. Pay special attention to the following:

- Make sure all brushes are of the same type and grade.
- Make sure all brushes are of the same length, neither too short nor too long to allow free movement in the brush holder.
- Check for free movement of brushes in the holder. Any rough particles in the face should be removed and the brush reseated.
- Check for suitable pressure against the commutator surface (usually between 1 and 2 psi).
- Seat the brushes by using sandpaper placed between the commutator surface and the brushes, with the rough side against the brush contact surface. Do not use emery cloth, as it will release a conductive grit that may become lodged between commutator segments, resulting in their shorting out.
- Repairing commutators is costly and requires that the machine be taken out of service. Brush replacement is quick and relatively inexpensive. Replace brushes regularly!

Commutator

The condition of the commutator is fundamental for the performance of DC motors. This means that the commutator must be checked regularly. Look for the following:

- The commutator must be kept free of oil and grease and the slots between the bars must be kept clean.
- Under normal operation condition, the film on the surface of the commutator will be a glossy, dark brown or slightly black colour.
- A polished copper surface or surface wear indicates that the brushes must be replaced.
- A black and thick colouring, which usually occurs due to long overloads with humidity, indicates that there is excessive patina on the commutator. Do not use emery cloth to remove the patina. Instead, use sandpaper or an appropriate milling wheel.

Mechanical faults

Mechanical faults can result in overheating or excessive vibration. Common mechanical faults include:

- Worn bearings
- Armature imbalance

- Improper alignment of the motor and the mechanical load
- Loose coupling between the motor and load
- Loose mounting bolts
- Unbalanced mechanical load

Regular maintenance includes cleaning, lubricating and routine inspection of the mechanical condition of the motor and drive system.

Shaft alignment

Proper alignment of a generator's shaft with its prime mover is critical for minimizing vibration and extending bearing life. An armature shaft that moves up and down freely indicates worn bearings. Check alignment using devices designed for the purpose, specifically dial indicators and laser aligners.

Proper maintenance is the best way to ensure the correct operation and reliability of a motor. Table 1 below gives a typical maintenance schedule for a DC motor.

Table 1 Maintenance schedule

COMPONENT	WEEKLY	MONTHLY	6 MONTHS	YEARLY
Brushes and brush rigging	• Good visual inspection. • Check for brush wear. • Check for proper seating of brushes. • Check the condition of brush holders (look for loose bolts and wear). • Check condition of pigtail shunts.	• Check length of brushes. • Replace brushes when manufacturer's wear mark disappears. Replace with same type and grade of brushes. • Check for normal wear and free movement in the brush holder. Replace cracked and broken brushes. • Remove some brushes to check contact with commutator surface. • Clean brushes and brush holders with vacuum cleaner or jet of dry air.		

COMPONENT	WEEKLY	MONTHLY	6 MONTHS	YEARLY
Commutator	• Good visual inspection. • Check commutator condition and wear.	• Check formation of film. Commutator must be glossy with a slightly dark colour like well-done toast. • Loose brushes cause sparking, overheating and excessive wear of the commutator and brushes. • Check height of mica between commutator bars.	• Check commutator surface and the condition of the film. A black coloration or streaks in the film indicate commutation problems.	
Bearings	• Listen for bearing noise. If bearing sounds noisy, check with screwdriver or stethoscope.	• Check for leakage of grease in the bearing housing. Clean it before operating the motor. • Check for bearing noise. Replace noisy bearings. • If required, re-grease according to manufacturer's recommendations.	• Check for noise on both bearings. • Replace noisy bearings. • Remove external bearing caps to check grease. • Follow manufacturer's recommended lubrication intervals.	• Detailed analysis of bearings. Follow manufacturer's recommended lubrication intervals.

Table 2 lists the common characteristics of a malfunctioning DC motor, the probable cause and corrective measures for each situation.

Table 2 Troubleshooting

MALFUNCTION	PROBABLE CAUSES	CORRECTIVE MEASURES
Motor does not start, unloaded	• Armature circuit open • Short in the interpole coil or in the armature • Drive system defective • Brush holder not at neutral plane • Field circuit open	• Test armature for opens and shorts. • Check for break or defect in the drive system. • Set brushes to neutral plane. • Find and repair open.
Motor starts bumping	• Drive system defective • Short in armature coils • Short between commutator bars	• Check for break or defect in the drive system. • Repair armature. • Check commutator and clean between bars.
Motor starts but stalls when load is applied	• Short in armature coils • Excess line drop • Brushes not at neutral plane • Drive system incorrectly adjusted	• Repair armature. • Check supply voltage and line drop. • Reset brushes position to the neutral plane.
Motor overspeeds and speed fluctuates when load is applied	• Brushes not at neutral plane • Field circuit open or no-load field rheostat set too high • Auxiliary series winding incorrectly connected, differentially compounding	• Reset brushes position to the neutral plane. • Repair the open. Lower field rheostat below critical resistance value. • Check connection and correct it.
Motor overheats during operation	• Overload • Insufficient air flow • Short circuit in the armature or field winding	• Check fan rotation and direction, clean air pipes and/or filters. Replace filters, if required. • Check windings and commutator solder points. • Repair the coils.
Overheating bearing	• Excess grease • Deteriorated or incorrect grease • Bad bearing • Excessive speed or load	• Remove excess grease. • Re-lubricate with correct grease. • Replace the bearings. • Reduce speed or decrease load.

MALFUNCTION	• PROBABLE CAUSES	• CORRECTIVE MEASURES
Excessive sparking at brushes when load is applied	• Dirty commutator surface • Grooves or striations on the commutator surface • High insulation between bars (mica) • Insufficient brush pressure • Loose brushes • Brushes are below wear marks • Brush grade or type wrong for load • Brush rigging broken • Brushes incorrectly set • Brushes frozen in the holder • Brushes not at neutral plane • Short circuit between commutator bars	• Machine the commutator, lower the mica and polish copper bar wedges. • Clean the commutator surface with a polishing stone (“stone commutator”). • Adjust brush position in relation to load. • Check brush pressure. • Replace brush holder. • Use brushes specified for type of load. • Replace brushes. • Put sandpaper on the commutator surface and seat the brushes. • Check dimensional tolerance of brushes. • Adjust brushes, following their markings. • Find and eliminate short circuit.
Sparking on one brush holder arm or all on brushes	• Error in the distribution of brushes • Uneven distribution of current • Poor contact	• Check location of brush holders. • Check air gap uniformity of the interpoles. • Retighten bolts.
Excessive sparking when load increases	• Brushes not at neutral plane • Overload	• Adjust overload settings to lower value. • Reset brushes position to the neutral plane.

☑ Now do Self-Test 1 and check the answers

Self-Test 1

1. When operated correctly, a DC motor should run without ____________________ ,
   ___________________________ and ___________________________

2. List three typical electrical faults associated with DC motors.

3. Continuity tests of the armature and field circuits can be used to locate
   ____________________.

4. Which of the following test equipment is most effective in conducting insulation tests?
   a. ohmmeter
   b. wheatstone bridge
   c. megger
   d. continuity tester

5. A ____________________ is often used to test for shorted coils on an armature.

6. List three common mechanical faults of a DC motor.

7. Regular mechanical maintenance should include ____________________ ,
   _____________________ and _____________________________________ .

8. A ______________ is often used to detect improper alignment of a motor (and the mechanical load).

9. List five causes of excessive brush sparking.

Answer Key

Self-Test 1

1. overheating, sparking at the brushes, excessive vibration
2. open circuit, short circuit, ground, incorrect connection, improper voltage
3. open circuits
4. c. megger
5. growler
6. worn bearings, unbalanced armature, improper alignment, loose coupling, loose mounting bolts
7. cleaning, lubricating, inspection
8. dial indicator
9. dirty commutator surface, grooves or striations on the commutator surface, high insulation between bars (mica), insufficient brush pressure, loose brushes, brushes are below wear marks, wrong brush grade or type for load, brush rigging broken, brushes incorrectly set, brushes frozen in the holder, brushes not at neutral plane, short circuit between commutator bars

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